CHARLES UNIVERSITY
IN PRAGUE

FACULTY OF SCIENCE
Department of Physical Geography and Geoecology

Mgr. Aleš Urban

Spatial patterns of links between temperature extremes and cardiovascular mortality in the Czech Republic

Prostorové vzory vazeb mezi teplotními extrémy a úmrtností
na kardiovaskulární nemoci v ČR

Ph.D. thesis

Supervisor: RNDr. Jan Kyselý, Ph.D.

Prague 2016

Acknowledgement

First of all, I would like to express my gratitude to my supervisor, Dr. Jan Kyselý, for the professional guidance, critical feedback, patience, and continuous support throughout my Ph.D. studies. I am very grateful for the opportunity to participate in his project that enabled me to gain valuable international experience. My thanks go also to Dr. Katrin Burkart, Dr. Christian Schuster, and prof. Tobia Lakes for their useful advice, suggestions and feedback during my traineeship at the Department of Geography, Humboldt University in Berlin. I am thankful to Dr. Hana Hanzlíková and Dr. Eva Plavcová for their help with preparing epidemiological datasets and useful discussions concerning their interpretation and analyses. Special thanks go to all anonymous reviewers whose valuable comments considerably improved the quality of the papers. I thank the Institute of Atmospheric Physics CAS for excellent working conditions and support of my scientific work. Finally, I am grateful to my family for their unconditional support and confidence.

The study was supported by the Czech Science Foundation, project P209/11/1985, and partly by the Charles University Grant Agency, project no. 3300-243-227 249. The traineeship at Humboldt University in Berlin was supported by the Erasmus+ program.

I declare that I carried out work on this doctoral thesis independently and only with the cited sources, literature and other professional sources. Neither this thesis nor any substantial part within have been submitted for the purpose of obtaining the title of Ph.D. or any other title at another institution.

In Prague, 20 May 2016

………………………………….
Mgr. Aleš Urban

Abstract

Spatial patterns of links between temperature extremes and cardiovascular mortality in the Czech Republic

Previous studies have examined relationships of high and low air temperatures to mortality due to cardiovascular diseases (CVDs) in the Czech Republic as a whole. Much less has been understood about possible regional differences in the heat and cold effects on mortality. Within four papers published in international peer-reviewed journals, the author of this thesis investigated links between extreme temperatures and CVD mortality in the Czech Republic while considering in particular differences between (i) urban and rural areas, (ii) regions with different socioeconomic status, and (iii) regions with different physical–environmental conditions. Various biometeorological approaches were compared in order to identify meteorological characteristics affecting heat- and cold-related mortality. Excess mortality was determined as differences between observed and expected daily values, the latter being adjusted for long-term changes, annual and weekly cycles, and epidemics of influenza/acute respiratory infections. Air temperature, biometeorological indices (including the Universal Thermal Climate Index, Apparent Temperature, and Physiologically Equivalent Temperature), and Spatial Synoptic Classification were applied in order to identify days/spells with heat and cold stress and their climatological characteristics.

Generally higher relative excess CVD mortality on hot days than on cold days was found in both urban and rural regions. After taking into account lagged effects of temperature on excess mortality, however, the effect of hot spells was significant in highly urbanized regions while most excess deaths in rural districts may be attributed to harvesting effects. Highest population count and density, highest average temperature due to low altitude, and generally worst thermal conditions due to high proportion of artificial surface were the factors associated with largest excess CVD mortality due to hot spells in urban districts. The peak in excess CVD mortality was observed on the day after the hot spell's onset, which was associated with a transition between oppressive weather types. While heat effects on CVD mortality for air temperature and the examined thermal indices were similar, air temperature provided a weak cold effect in comparison with the thermal indices including the wind chill effect. Only within the most deprived regions did socioeconomic status play a significantly relevant role.

Results of the thesis are potentially useful for better targeting biometeorological forecasts and warnings to population groups and regions especially vulnerable to extreme weather, as well as for estimating possible climate change effects on heat- and cold-related mortality in the Czech Republic. The study also highlights the importance of critically evaluating applicability and benefits of various biometeorological approaches using epidemiological data when defining criteria and algorithms for integrated warning systems.

Key words: heat stress; cold stress; mortality; spatial differences; cardiovascular disease

Shrnutí

Prostorové vzory vazeb mezi teplotními extrémy a úmrtností na kardiovaskulární nemoci v ČR

Předchozí studie prokázaly vliv období vysokých i nízkých teplot vzduchu na úmrtnost na kardiovaskulární onemocnění pro populaci České republiky (ČR) jako celku. Cílem této dizertační práce byl výzkum regionálních rozdílů v těchto vztazích a faktorů, které je ovlivňují. Ve čtyřech článcích publikovaných v mezinárodních recenzovaných časopisech byly zkoumány rozdíly ve vlivu vysokých a nízkých teplot na kardiovaskulární úmrtnost v ČR zejména mezi (i) městskými a venkovskými oblastmi, (ii) regiony s rozdílnou úrovní socioekonomické deprivace a (iii) oblastmi s odlišnými fyzicko-geografickými a environmentálními podmínkami. Tyto rozdíly byly zkoumány za využití různých biometeorologických přístupů s cílem určit meteorologické charakteristiky mající vliv na úmrtnost v důsledku stresu z horka a chladu. Vliv teploty vzduchu na úmrtnost byl stanoven na základě relativních odchylek od očekávaných denních počtů úmrtí v horkých a chladných dnech. Očekávaný počet úmrtí pro každý den byl stanoven ošetřením časových řad o nemeteorologické složky, jako jsou dlouhodobý trend, sezónnost, týdenní cykly v chodu úmrtnosti a dále epidemie chřipky a akutních respiračních infekcí. Horké (chladné) dny (resp. období) v létě (zimě) byly vymezeny pomocí kvantilů rozdělení teploty vzduchu a vybraných biometeorologických indexů (Universal Thermal Climate Index, Apparent Temperature a Physiologically Equivalent Temperature) v daném regionu. Pomocí synoptického přístupu (Spatial Synoptic Classification) byly zkoumány klimatologické charakteristiky horkých období z hlediska četnosti výskytu obtížných vzduchových hmot a jejich vlivu na úmrtnost.

Obecně vyšší odchylky úmrtnosti na CVD byly pozorovány v horkých než chladných dnech a to jak ve městech, tak na venkově. Při zohlednění tzv. efektu posunu úmrtnosti při výskytu horkých vln byl však celkový vliv období vysokých teplot vzduchu na zvýšenou úmrtnost významný pouze u městského obyvatelstva. Korelační analýza na úrovni okresů určila jako hlavní faktory prostorových rozdílů ve vlivu horkých dnů na kardiovaskulární úmrtnost vysoký počet obyvatel a hustotu zalidnění, teplé klima v důsledku nízké nadmořské výšky a obecně zhoršené tepelné podmínky v důsledku vysokého podílu nepropustných městských povrchů. Naopak míra socioekonomické deprivace měla statisticky významný vliv pouze v regionech s obecně nízkým socioekonomickým statusem. Klimatologická analýza průběhu horkých období ukázala možnou souvislost mezi charakteristickou změnou obtížných vzduchových hmot během kulminace horké vlny a výskytem maximálních odchylek úmrtnosti. Zatímco v případě horkých dnů byly zjištěny minimální rozdíly mezi výsledky pro jednotlivé biometeorologické indexy a teplotu vzduchu, v případě výběru chladných dní byly zjištěny značné rozdíly a zvýšená kardiovaskulární úmrtnost byla lépe podchycena při použití biometeorologických indexů uvažujících kromě teploty vzduchu i ochlazující účinek větru.

Výsledky dizertační práce jsou potenciálně užitečné pro zpřesnění biometeorologické předpovědi a zlepšení možností varování rizikových skupin obyvatelstva a regionů v případě výskytu extrémních teplot vzduchu. Tato zjištění mohou být zároveň použitelná i pro tvorbu scénářů možných budoucích změn úmrtnosti v důsledku stresu z horka nebo chladu. Studie porovnávající různé metodické přístupy také poukazují na důležitost kritického porovnání a validace těchto přístupů na epidemiologických datech pro vývoj biometeorologické předpovědi a integrovaných varovných systémů.

Klíčová slova: stres z horka; stres z chladu; úmrtnost; regionální rozdíly; kardiovaskulární onemocnění

List of publications used as parts of the dissertation

Seznam publikací použitých jako součást práce

Paper 1 Urban A, Davídkovová H, Kyselý J (2014) Heat- and cold-stress effects on cardiovascular mortality and morbidity among urban and rural populations in the Czech Republic. *International Journal of Biometeorology*, 58: 1057–1068. doi: 10.1007/s00484-013-0693-4. IF 3.246.

Paper 2 Urban A, Kyselý J (2014) Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic. *International Journal of Environmental Research and Public Health*, 11: 952–67. doi:10.3390/ijerph110100952. IF 2.063.

Paper 3 Urban A, Burkart K, Kyselý J, Schuster C, Plavcová E, Hanzlíková H, Štěpánek P, Lakes T (2016) Spatial patterns of heat-related cardiovascular mortality in the Czech Republic. *International Journal of Environmental Research and Public Health*, 13: 284. doi: 10.3390/ijerph13030284. IF 2.063.

Paper 4 Urban A, Kyselý J (2015) Application of spatial synoptic classification in evaluating links between heat stress and cardiovascular mortality and morbidity in Prague, Czech Republic. *International Journal of Biometeorology*. doi: 10.1007/s00484-015-1055-1. IF 3.246.

Table of contents

1 Summary ... 9
1.1 Introduction ... 9
1.2 Human thermal comfort ... 10
1.3 Evaluating temperature–mortality relationships ... 12
1.4 Goals and structure of the thesis ... 16
1.5 Data ... 17
1.6 Methods ... 18
1.7 Summary of results ... 19
1.8 Conclusions and outlook for future research ... 21
1.9 References ... 22
2 Heat- and cold-stress effects on cardiovascular mortality and morbidity among urban and rural populations in the Czech Republic ... 27
2.1 Introduction ... 27
2.2 Area of investigation, data, and methods ... 29
2.3 Results ... 34
2.4 Discussion ... 36
2.5 Conclusions ... 42
2.6 References ... 43
3 Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic ... 47
3.1 Introduction ... 47
3.2 Data and Methods ... 49
3.3 Results ... 52
3.4 Discussion ... 57
3.5 Conclusions ... 59
3.6 References ... 60
4 Spatial patterns of heat-related cardiovascular mortality in the Czech Republic ... 63
4.1 Introduction ... 63
4.2 Data and methods ... 65
4.3 Results ... 71
4.4 Discussion ... 76
4.5 Conclusions ... 80
4.6 References ... 81
5 Application of spatial synoptic classification in evaluating links between heat stress and cardiovascular mortality and morbidity in Prague, Czech Republic ... 85
5.1 Introduction ... 85
5.2 Data and methods ... 87

5.3 Results 90
5.4 Discussion 96
5.5 Conclusions 99
5.6 References 100

1 Summary

1.1 Introduction

Extreme temperature events are the deadliest atmospheric hazards in mid-latitudes (Kirch et al. 2005; EEA 2010). Especially periods of extremely high temperatures – heat waves – cause large numbers of victims in Europe, comparable only with such non-atmospheric hazards as earthquakes (EEA 2010). In 2003, an extreme heat wave in southwestern Europe resulted in more than 70,000 heat-related deaths (EEA 2010), and Barriopedro et al. (2011) reported similar estimates (55,000 fatalities) for the 2010 heat wave in Russia. In the Czech population, deviations of mortality from the baseline may exceed 100 deaths daily (more than a 30% relative increase) at heat wave peaks and reach several hundred deaths over long-lasting hot periods, such as the severe 1994 heat waves (Kyselý 2004). Similar estimates were reported for the 1994 heat wave in Berlin and Brandenburg (Gabriel and Endlicher 2011). Due to climate change, increasing frequency and magnitude of extreme heat waves are projected for the future (e.g., Gosling et al. 2009; IPCC 2014). In central Europe specifically, approximately 40% of July and August days at the end of the 21st century are projected to be extreme with respect to current climatic conditions (Ballester et al. 2009). Therefore, heat waves comparable to those in 1994, 2003, 2010, 2013 (Lhotka and Kyselý 2015), and 2015 (Russo et al. 2015) may represent common summer weather in a future central-European climate.

With respect to increasing frequency and magnitude of heat waves, increased heat-related mortality and decreased cold-related mortality are projected in a future climate (Gosling et al. 2009; Muthers et al. 2010; Huang et al. 2011). As many studies have shown, however, physiological, behavioral and technological adaptation may considerably reduce impacts of heat stress on human health (Christidis et al. 2010; Matzarakis et al. 2010; Kyselý and Plavcová 2012; Bobb et al. 2014; Ebi et al. 2014). That means there remains great uncertainty concerning the impact of climate change on weather-related mortality (Gosling et al. 2009; Huang et al. 2011; Gosling et al. 2012; Boeckmann et al. 2014). Moreover, the estimates of cold-related deaths (e.g., 1,900 deaths during 1998–2009 in Europe; EEA 2010) may be substantially underestimated inasmuch as the effect of cold spells is lagged and mortality may exceed expected values for several weeks (Huynen et al. 2001; Laschewski and Jendritzky 2002; Cheng and Su 2010; Kyselý et al. 2011). The attribution of excess mortality to low temperatures is not straightforward, however, because influenza/acute respiratory infections and decreased input of UVB radiation are factors contributing to the typical seasonal mortality cycle with a winter maximum (von Klot et al. 2012; Kinney et al. 2015).

1.2 Human thermal comfort

Human thermal comfort is a complex phenomenon created by diverse interactions between physiology, psychology, and behavior (Yao et al. 2009). Balancing the human heat budget is controlled by an autonomous thermoregulatory system that is supported additionally by behavioral adaptation (e.g., eating and drinking, activity and resting, clothing, exposure, housing, migration) (Jendritzky et al. 2012). The heat exchange between the human body and its environment takes place by sensible and latent heat fluxes, radiation, and conduction (Figure 1.1). Atmospheric parameters governing all of the aforementioned heat fluxes include air temperature, water vapor pressure, wind velocity, and mean radiant temperature (Tmrt). Tmrt summarizes all short-wave and long-wave radiation fluxes reaching the human body, and it is the most important parameter influencing outdoor thermal comfort during sunny conditions (Kántor and Unger 2011). However, calculation of Tmrt is affected by great uncertainties if accurate meteorological data are not available (Weihs et al. 2012). Thermal comfort in cold environments, on the other hand, is markedly worsened by high wind speed – the so-called wind chill effect (Shitzer et al. 2012). In addition, metabolic rate (physical activity) and clothing insulation worn by the subject are important non-meteorological factors modifying human thermal comfort (Jendritzky et al. 2012).

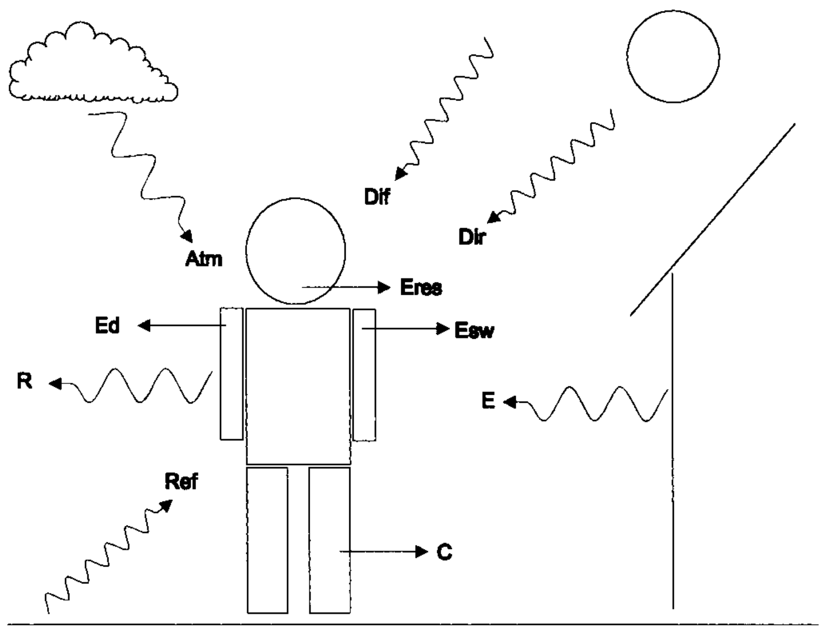

Figure 1.1 Components of the energy balance of humans. C, convective and conductive heat flux; Ed, latent energy flux by vapor diffusion; Esw, latent energy flux by sweat evaporation (perspiration); Eres, energy flux by respiration; Atm, long-wave atmospheric counter radiation; Dir, direct solar radiation; Dif, diffuse radiation; Ref, short-wave reflected radiation; R, long-wave radiation of humans; E, long-wave radiation from surrounding areas (taken from Becker 2000).

The aforementioned knowledge is reflected in the development of human thermal comfort models that numerically solve the human heat budget. The heat-budget thermal comfort models are based on thermo-physiological models such as the Klima-Michel model (KMM; Jendritzky et al. 1979; Jendritzky and Nübler 1981) or the advanced Fiala model (Fiala et al. 2010) and the state-of-the-art adaptive clothing model (Havenith et al. 2011). Output of such models is an equivalent temperature (human thermal comfort index) representing intensity of physiological strain with respect to reference conditions. Many thermal comfort models and derived indices have been developed since Fanger's (1972) Predicted Mean Vote model. Human thermal comfort indices used widely in recent biometeorological assessments include Physiologically Equivalent Temperature (PET; Höppe 1999; Matzarakis et al. 2007), based on the Munich Energy-Balance Model for Individuals (MEMI) (Höppe 1984), and Perceived Temperature (PT; Staiger et al. 2012), derived from the KMM, being used operationally by the German Weather Service (DWD, Jendritzky et al. 2000). The recently developed Universal Thermal Climate Index (UTCI), derived from the Fiala model and adaptive clothing model (Figure 1.2), takes account of state-of-the-art knowledge in all associated disciplines (physiology, occupational medicine, physics, meteorology, and biometeorological and environmental sciences). It was developed as part of COST Action 730 in order to create a standard outdoor thermal conditions measure suitable for various applications of human biometeorology (Jendritzky et al. 2012; McGregor 2012). In comparison with other indices, UTCI is more sensitive to even slight changes in meteorological inputs and describes better various climatic conditions (Błażejczyk et al. 2012). Nevertheless, only a few studies have evaluated how UTCI performs compared to other indices in assessing epidemiological outcomes, and their results have been unconvincing (Burkart et al. 2011; Nastos and Matzarakis 2011; Morabito et al. 2014).

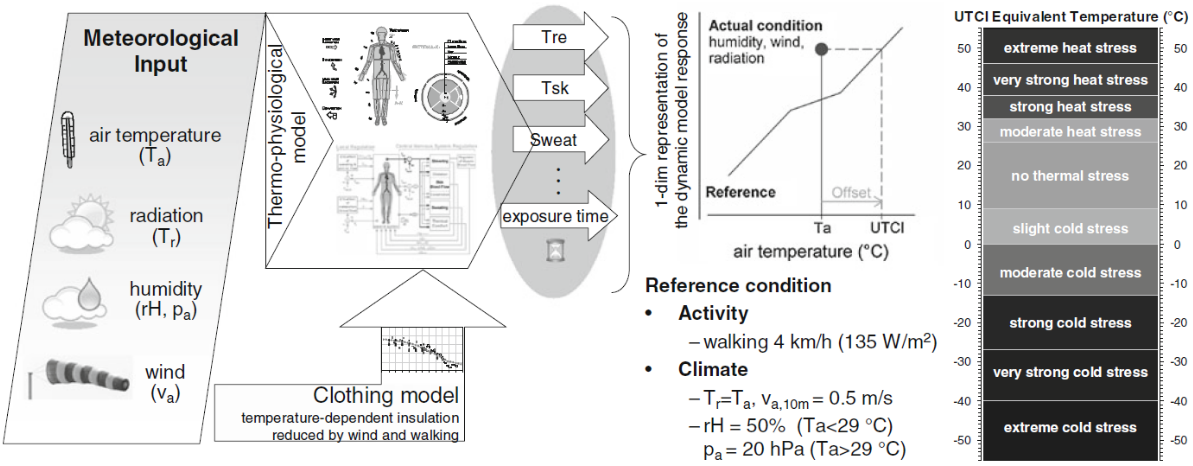

Figure 1.2 Concept of UTCI derived as equivalent temperature from the dynamic multivariate response of the thermophysiological UTCI-Fiala model (Fiala et al. 2012) coupled with a clothing model (Havenith et al. 2012) (taken from Bröde et al. 2012).

Generally, no significant predictive advantage for any thermal index (including UTCI) has been observed over the use of air temperature (Kim et al. 2011; Vaneckova et al. 2011).

While human thermal comfort indices refer to a reference healthy person, the population groups most affected by thermal stress are the elderly, young children, and persons with impaired thermoregulation due to poor physical and medical condition (Kenny and Munce 2003). The extent to which human health outcomes such as mortality are connected to the human heat balance is the crucial question of studies assessing temperature–mortality relationships (Burkart et al. 2011). Moreover, the determination accuracy of human thermal comfort indices is limited due to the aforementioned uncertainties in modelling Tmrt. Therefore, air temperature or simple indices, derived empirically from combined effect of air temperature, humidity, and/or wind velocity (e.g., Apparent Temperature (AT); Steadman 1984) on the human organism, have still been widely used as proxy variables representing biometeorological conditions (Basu 2009). Their advantages lie in their little demand for input data, easy predictability for weather forecasters, and clarity for public and health information providers (McGregor 2011).

The limitations associated with a lack of appropriate input data for thermal comfort indices can to some extent be avoided by taking a synoptic approach. Such a methodology takes into account the entire suite of daily weather elements (air temperature, a humidity variable, total cloud amount, wind components, and atmospheric pressure) that are classified into air masses (weather types) with meteorologically homogeneous conditions (Davis and Kalkstein 1990). Spatial synoptic classification (SSC; Kalkstein et al. 1996; redeveloped by Sheridan 2002) has been widely employed in various biometeorological applications, and particularly in developing heat-and-health-warning systems (Sheridan and Kalkstein 2004; Hondula et al. 2014). These systems are based on identifying so-called oppressive air masses associated with increased risk of death due to hot weather that follows issuance of an alert. Benefits of such warning systems have been documented in saving both human lives and costs (Toloo et al. 2013). Despite the availability of an SSC calendar in Europe (Bower et al. 2007), gaps in both research and application of SSC in central Europe have been mentioned in international literature (Hondula et al. 2014).

1.3 Evaluating temperature–mortality relationships

1.3.1 Baseline mortality estimation

In order to identify short-term effects of temperature on health, adjustments must be made in the time series for long-term trend and seasonality (Bhaskaran et al. 2013). The effects of extremely high/low temperatures can be subsequently estimated as differences between observed mortality and the adjusted baseline (expected) mortality during individual hot/cold events. Numerous methods have been used for calculating the mortality baseline (see Gosling et al. 2009). The most common approaches (see Figure 1.3) include time-stratified models splitting the study period into intervals (year, day of year) and estimating an average number of deaths for each interval (cf. Kyselý 2004), as well as generalized linear and generalized additive models using a flexible spline function of time, flexibility of which is defined by degrees of freedom (Wood 2006; Bhaskaran et al. 2013).

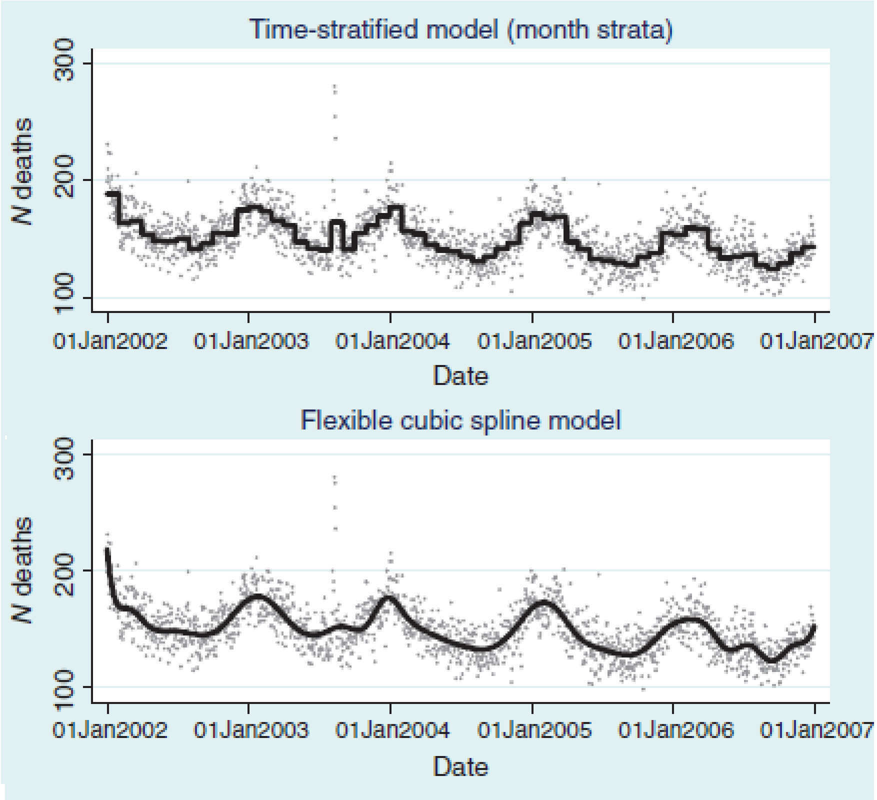

Figure 1.3 Two alternative ways of modelling long-term patterns in data (seasonality and trends) (taken from Bhaskaran et al. 2013).

After adjusting health data for seasonality and long-term patterns, the relationships between model residuals and temperature can be investigated by adding the exposure variables (air temperature, air pollution, etc.) directly into the model and examining the regression relationships – i.e., the so-called "relative risk" of increase in mortality for each 1°C increase/decrease in temperature above/below a certain threshold (Hajat et al. 2007; Bhaskaran et al. 2010; Burkart et al. 2011). Other studies prefer to evaluate temperature–mortality associations by calculating excess mortality, thereby leading to what are termed "rate ratios" between observed and expected numbers of cases above/below a specific threshold defining hot and cold periods (e.g., the 5th/95th percentile of daily temperature; Huynen et al. 2001; Gabriel and Endlicher 2011; Kyselý et al. 2011; Ma et al. 2013).

1.3.2 Temporal patterns

In addition to a direct effect of thermal discomfort on a specific day, its temporal displacement is of major interest in this kind of research. While during heat waves excess mortality often occurs for several days which are then followed by a decrease of mortality rates to below-expected levels (so-called "mortality displacement" or "harvesting" effect; Gosling et al., 2009), no significant decrease below expected mortality has been observed during/after cold spells. Although magnitudes of the short-term mortality displacement during heat waves have been observed to vary considerably among populations of different cities (Gosling et al. 2007; Basu 2009; Baccini et al. 2013; Saha et al. 2014; Zaninovic and Matzarakis 2014), studies assessing spatial variability in temperature-related mortality in a specific geographic area do not usually address the harvesting issue.

1.3.3 Spatial patterns

Previous studies have reported a nonlinear association between ambient temperature and mortality, with one or more change points defining temperatures above/below which the heat/cold-related mortality risks significantly increase (Curriero et al. 2002; Burkart et al. 2011; Wu et al. 2013) (Figure 1.4). Temperature thresholds of significantly increasing mortality risk usually vary by location and are strongly associated with latitude (Curriero et al. 2002; Braga et al. 2002; Baccini et al. 2008) due to different technological (central heating, air conditioning) and behavioural (e.g., clothing) adaptations (Eurowinter Group 1997; Gosling et al. 2009).

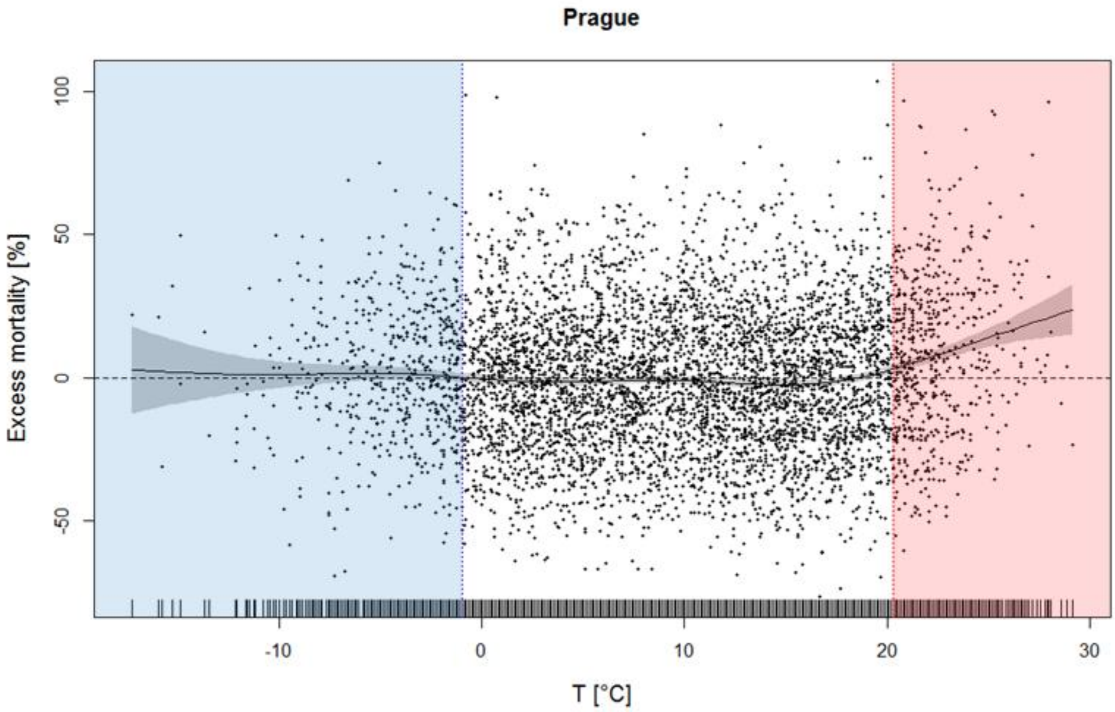

Figure 1.4 Nonlinear relationship between relative excess CVD mortality and mean daily temperature in Prague during 1994–2009 represented by a thin plate regression spline. The gray area represents 95% confidence bounds of the regression spline. The red/blue polygon depicts days with air temperature above/below the 90th/10th percentile of the temperature distribution.

Until now, most studies have investigated effects of heat waves among urban populations (Vandentorren et al. 2004; Kirch et al. 2005; Hajat et al. 2006; McMichael et al. 2008), which are most affected by heat-related mortality (O'Neill et al. 2009; Tan et al. 2010; Gabriel and Endlicher 2011). Urban residents face heightened heat stress due to altered water and energy balances – the so-called "urban heat island" effect (Oke 1982). Land-cover characteristics such as the amount of impervious surface, green space, and unvegetated areas in a neighbourhood have been associated with increased heat vulnerability (Reid et al. 2009; Uejio et al. 2011; Bao et al. 2015) and heat-related mortality (Xu et al. 2013; Klein Rosenthal et al. 2014; Burkart et al. 2015). Moreover, synoptic conditions typical for the formation of heat waves (Kyselý 2008) favour elevated concentrations of such air pollutants as tropospheric ozone (O_3) and particulate matter (PM_{10}). Causality of relationships among temperature, air pollution, and human health is associated with great uncertainty (Buckley et al. 2014). The effect of air pollution on mortality is often reported to be relatively small and insignificant compared to that of air temperature (Basu 2009; Vaneckova et al. 2011). Nevertheless, high levels of air pollutants may significantly strengthen the impacts of high temperatures on human health (Burkart et al. 2013).

Generally, people with impaired thermoregulation due to poor physical and health conditions (Kenney and Munce 2003), often associated with chronic diseases of the cardiovascular or respiratory system (McMichael et al. 2006; Basu 2009; Davídkovová et al. 2014), are most vulnerable to thermal stress. Therefore, demographic and socioeconomic factors are considered to be significant spatial modifiers of weather–mortality relationships (Sheridan and Dolney 2003; Wu et al. 2010; Burkart et al. 2011; Hattis et al. 2012). Higher proportions of elderly, socially deprived (homeless, unemployed), and/or isolated populations (people living alone, immigrants, ethnic minorities) are factors associated with vulnerability to thermal discomfort (Gosling et al. 2009; O'Neill et al. 2009; Conlon et al. 2011).

Although cold effects on excess mortality have been found to be stronger among rural than urban populations due to larger wind chill effect (Hajat et al. 2007; Gómez-Acebo et al. 2010; Conlon et al. 2011), heat stress is presumed to be a significant risk factor for the rural population as well (Gabriel and Endlicher 2011). To date, there exist only a few studies investigating spatial differences in weather–mortality relationships under given climatic conditions (i.e., in relatively small territorial units) including urban as well as rural populations (cf. Hajat et al. 2007; Gabriel and Endlicher 2011; Hattis et al. 2012; Maier et al. 2014; Kovach et al. 2015). Moreover, none of the aforementioned studies considered the effects of physical–geographic conditions such as local climate and topography on heat/cold-related mortality.

1.3.4 State-of-the-art knowledge in the Czech Republic

So far, studies in the Czech Republic have investigated climatology of extreme temperature events (e.g., Kyselý 2002; Kyselý 2010) and examined their effects on excess total mortality and mortality due to cardiovascular diseases (CVDs) (Kyselý 2004; Kyselý and Huth 2004; Kyselý and Kříž 2008; Kyselý et al. 2009; Plavcová and Kyselý 2010; Kyselý et al. 2011) while considering the population of the Czech Republic as a whole. The elderly, women, and people with chronic CVDs were found to comprise the population groups with the largest heat-related mortality (Kyselý et al. 2011; Davídkovová et al. 2014), while middle-aged men and those with acute CVDs were most vulnerable to cold (Kyselý et al. 2009; Davídkovová et al. 2014). Dzúrová (1993) demonstrated significant relationships between environmental deprivation, social deprivation, and poor health condition within the population of the Czech Republic. Relationships between socioeconomic status and cardiovascular risk factors have been documented in the Czech Republic as well (Bobak et al. 1999; Dragano et al. 2007). Nevertheless, spatial patterns in temperature–health relationships taking into account demographic, socioeconomic and physical–environmental factors in a comprehensive way have not yet been investigated in the Czech Republic.

1.4 Goals and structure of the thesis

The main objective of this dissertation is to analyze regional differences in links between extreme temperatures and CVD mortality in the Czech Republic, and especially differences between (i) urban and rural areas, (ii) regions with different socioeconomic status, and (iii) regions with different physical–environmental conditions. In addition, various biometeorological approaches are employed for identifying meteorological characteristics important for heat- and cold-related mortality assessment. These topics are comprehensively investigated and discussed in four papers published in international peer-reviewed journals. As first author of all papers, A. Urban was responsible for gathering, cleaning and spatial analysis of the socioeconomic and environmental data, defining the analytical approach, performing most analyses, preparing initial interpretation of results, and drafting manuscripts of all papers. J. Kyselý, as supervisor of the thesis and the main co-author of the papers, defined the initial focus of the studies, contributed to defining the approach to the analyses, and provided critical revisions and feedback during the entire research. Other co-authors of the papers contributed to carrying out the research design (K. Burkart, C. Schuster, T. Lakes), gathering and cleaning the epidemiological data as well as assistance with interpretation of physiological mechanisms causing different responses to heat and cold stress (H. Davídkovová/Hanzlíková), gathering and gridding the temperature data (P. Štěpánek), and performing advanced statistical calculations in R (E. Plavcová). All co-authors contributed to critical revisions of the manuscripts. Specific authors' contributions are defined in individual papers.

Inasmuch as the effects of cold stress on mortality are less straightforward and, on the other hand, heat stress has been considered a greater threat in relation to climate change, the bulk of the papers focus on heat-related mortality. While CVD mortality was the main focus of this thesis, additional analyses of heat and cold effects on CVD morbidity (hospital admissions) were carried out in two papers.

The papers included within the thesis are as follow:

- Paper 1: "**Heat- and cold-stress effects on cardiovascular mortality and morbidity among urban and rural populations in the Czech Republic**" (Urban et al. 2014) compares the effects of heat and cold stress on CVD mortality and morbidity and examines differences in these effects between an urban and a rural region;

- Paper 2: "**Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic**" (Urban and Kyselý 2014) investigates differences in heat- and cold-related CVD mortality evaluated in terms of different thermal indices and compares their abilities to identify days with increased mortality risk;
- Paper 3: "**Spatial patterns of heat-related cardiovascular mortality in the Czech Republic**" (Urban et al. 2016) investigates spatial and temporal patterns in effects of high temperatures on CVD mortality in the Czech Republic with respect to demographic, socioeconomic, and physical–environmental factors;
- Paper 4: "**Application of spatial synoptic classification in evaluating links between heat stress and cardiovascular mortality and morbidity in Prague, Czech Republic**" (Urban and Kyselý 2015) employs the synoptic classification approach in order to examine associations between excess CVD mortality in Prague and hot spells with respect to their synoptic climatology.

1.5 Data

Epidemiological and meteorological time series necessary for the research were provided by the National Institute of Public Health (NIPH), the Institute of Health Information and Statistics (IHIS), the Czech Statistical Office (CZSO), and the Czech Hydrometeorological Institute (CHMI). The following time series were used for the analyses:

- daily numbers of deaths and hospital admissions due to cardiovascular disease (CVD, I00–I99 according to ICD-10 [International Classification of Diseases, 10th revision]) in the Czech Republic during 1994–2009, stratified by age, sex, and district of residence of every deceased person (data sources: NIPH, CZSO, and IHIS);
- daily climatic data (measured at 7:00, 14:00, and 21:00 local time) during 1994–2009 at 18 stations in the Czech Republic, including variables needed for calculating biometeorological indices (air temperature, dew point temperature, relative humidity, cloud cover, wind speed) (data source: CHMI);
- GriSt data set (described in Kyselý and Plavcová 2010): high-resolution gridded daily temperature (mean, minimum, and maximum) data covering the Czech Republic, interpolated from irregularly spaced meteorological stations operated by CHMI for 1994–2009 (data source: CHMI);
- daily data on air pollution (PM_{10}, O_3) in Prague during 1994–2009 (data source: CHMI);
- daily calendar of the spatial synoptic classification (SSC) for Prague, available from the SSC home page (http://sheridan.geog.kent.edu/ssc.html).

In order to identify regions with different demographic, socioeconomic, and physical–environmental characteristics, the following categorical data were used:

- Census 2001 database for individual districts in the Czech Republic (provided by the Czech Statistical Office);
- land cover characteristics from the CORINE land cover 2000 database (obtained from the Czech Environmental Information Agency (CENIA));
- characteristics from the ArcČR® 500 geographic database (provided by ARCDATA PRAHA).

1.6 Methods

The methods employed in the research are comprehensively described in individual papers. The basic steps that are common to all analyses are described below as they are essential for understanding the methodological approach as a whole.

1.6.1 Excess mortality quantification

In Papers 1, 2, and 4, the time-stratified model by Kyselý (2004) was employed for the baseline mortality estimation. This model is based on a multiplicative decomposition of time series with components of long-term trend, annual and weekly cycles, and residuals. In Paper 3, a single location-stratified generalized additive model ("mgcv" package in R (version 2.15.2)) (Wood 2006) with a flexible spline function was used in order to adjust mortality data for long-term trend and seasonality. Seven degrees of freedom per year were used as a common choice for daily mortality data (Bhaskaran et al. 2013). Weekly cycles were controlled by a categorical variable for day of week. In order to determine daily baseline mortality for individual districts, an additional categorical variable defining a district was added into the model formula. This approach allowed us to model baseline mortality consistently in all districts and helped to deal with small population counts in individual districts. In both approaches, relative deviations from the baseline mortality were used for evaluating mean excess mortality on days with hot/cold thermal conditions.

1.6.2 Hot and cold days

Hot (alternatively warm)/cold days with average (equivalent) temperature (AT, PET, and UTCI) above/below the 90th/10th percentile of the empirical distribution in summer (June–August)/winter (December–February) seasons over 1994–2009 were calculated. The 90th percentile was chosen instead of the 95th percentile because it yields a larger sample size, and that is beneficial for analyzing small population samples. Use of the percentile method (unlike determining an exact temperature threshold) allows for examining approximately the same sample sizes in different regions and at both temperature extremes. This method has commonly been used for regional comparison of heat and cold impacts on human health in different regions (Hajat et al. 2007; Gabriel and Endlicher 2011). In Papers 3 and 4, hot spells were defined as at least two consecutive days with average temperature above the 90th/95th percentile of its distribution in summer seasons (June–August) 1994–2009 in order to investigate lagged patterns of excess mortality (Paper 3) and climatological characteristics of hot spells (Paper 4). Mean daily (equivalent) temperature was employed for the definition because there was no single temperature measure superior to the others when the association between temperature and mortality was examined (Barnett et al. 2010).

1.7 Summary of results

1.7.1 Heat and cold effects on cardiovascular mortality and morbidity and their regional differences

Within the four papers, various aspects of heat and cold stress effects on CVD health in the Czech Republic were examined. Paper 1 brought new insights into which parts of the population are vulnerable to heat and cold, as well as what differences between heat- and cold-related effects on mortality and morbidity are typical. Generally higher relative excess CVD mortality was identified on hot days than on cold days in both an urban (Prague) and a rural (southern Bohemia) region (Figure 2.2). The analysis of regional differences showed highest vulnerability to heat stress among urban population with chronic CVDs, while the effects of cold stress were most pronounced on acute CVDs in the rural region. These findings were further complemented and supported by results for the population of the Czech Republic as a whole (Davídkovová et al. 2014) and may be useful for issuing better-targeted heat- and cold-stress alerts. Possible influences of both environmental (urban heat island effects and generally local climate, different exposure to air pollution) and socioeconomic (different population structure and level of socioeconomic deprivation) factors were further investigated in Paper 3. In contrast to mortality, weak excess CVD morbidity was observed for both hot and cold days (Figure 2.3). This may reflect the considerable number of people who die before they can be admitted to hospital, another primary cause for hospital admission (heat stroke, dehydration), or an increase in emergency visits in relation to less-severe incidents which might account in part for the effect of temperature on morbidity.

1.7.2 Benefits of thermal indices in evaluating heat and cold effects on mortality

In Paper 2, a follow-up analysis to Paper 1 investigated the ability of UTCI and other thermal indices (PET, AT) to identify days with significant excess CVD mortality. While similar heat effects for air temperature and thermal indices were found in both regions (Prague and southern Bohemia), differences in cold effects between individual indicators were much larger (Figure 3.2). In particular, UTCI selects windy winter days over the most freezing ones (Table 3.6). That resulted in a small effect on excess mortality (when UTCI was used) in the urban population that is sheltered from the effects of wind and, by contrast, the largest effect (among the examined indices) on excess mortality in the rural population (Table 3.5). These findings raise an issue as to the representativeness of wind speed measurements in the UTCI calculation, especially when urban environments are considered. AT (requiring only standard meteorological data) and PET appear to be more universal indicators in heat- and cold-related mortality assessments than is UTCI.

Generally, even as air temperature seems to be an appropriate tool for heat-related mortality assessment, it appears to be insufficient when effects of cold on epidemiological outcomes are considered, and thermal indices including the wind chill effect yield higher and probably more realistic cold-related mortality. This raises also a critical issue regarding the credibility of projections as to the impact of climate change on cold-related mortality when air temperature is used as the simplest proxy variable (cf. Gosling et al. 2011).

1.7.3 Spatial patterns of heat-related mortality

As the effects of heat stress on mortality were generally more significant than those of cold stress in both urban and rural areas, the following study (Paper 3) focused on analysis of spatial and temporal patterns of heat-related CVD mortality in the Czech Republic. Highest population count and density, highest average temperature due to low altitude, and generally worst thermal conditions due to high proportion of artificial surface were the factors associated with largest effects of heat on excess cardiovascular mortality in urban groups of districts (4.4, 4.6, and Table 4.3). The analysis of temporal patterns of mortality deviations during two weeks after a hot spell's onset revealed no mortality displacement in large municipalities, while most of the excess deaths in rural districts might be attributed to the mortality displacement effect (Figure 4.7). A significant relationship between decreased socioeconomic status and increased heat-related mortality was found only within the most deprived district group (Figure 4.5). Long-term exposure to highest environmental and socioeconomic deprivation within the Czech Republic in urban districts with low socioeconomic status (northwest Bohemia, Ostrava region) may be associated with higher percentage of people having chronic cardiovascular disease (cf. Paper 1). Inasmuch as coal mining and associated heavy industry (electricity generation, metallurgy) are typical economic activities in these districts, their populations are potentially at risk of increasing social deprivation in future due to economic transformation. The results highlight the role of social and environmental conditions in adaptability to heat across the population.

1.7.4 Synoptic approach to evaluating heat-related mortality

In the last paper (Paper 4), a synoptic approach was employed in order to investigate relationships between mortality and meteorological patterns associated with hot spells in Prague. The widely used spatial synoptic classification (SSC) was utilized for this purpose for the first time in central Europe. Two SSC air masses (AMs) – dry tropical (DT) and moist tropical (MT) – were found to be oppressive (OAMs), i.e., associated with significant excess CVD mortality (Figure 5.1, Table 5.3). DT is characterized by the highest air temperature and smallest cloud cover, wind speed and relative humidity among the AMs, while the more frequent MT type has on average lower air temperature but greater cloud cover and relative humidity than does DT (Table 5.2). Links between the OAMs and excess mortality are related to conditions on preceding days, as AMs occur in typical sequences during hot spells. DT is the most frequent AM at the beginning while MT occurs most frequently in a later phase of hot spells (Figure 5.4). The typical transition from DT to MT weather within hot spells in Prague was associated with the highest mean temperature deviation, largest day-to-day pressure drop, highest occurrence of OAMs (considered together), and highest mean excess CVD mortality. The results suggest that weather type transition may be the leading factor in timing of the CVD mortality peak within a hot spell (Figure 5.5).

1.8 Conclusions and outlook for future research

The results of the thesis bring new insights into heat- and cold-related cardiovascular (CVD) mortality and morbidity assessment under temperate climatic conditions and the applicability of various approaches for estimating heat and cold effects on populations living in different environments.

The main findings of the thesis are as follow:

- Generally higher relative excess CVD mortality was identified on hot days than on cold days in both urban and rural regions.
- However, while no mortality displacement in large municipalities after a hot spell's onset was observed, most of the excess deaths in rural districts might be attributed to the harvesting effect.
- Highest population count and density, highest average temperature due to low altitude, and generally worst thermal conditions due to high proportion of artificial surface were the factors associated with largest excess CVD mortality due to hot spells in urban districts.
- The highest excess CVD mortality was observed on the day after the hot spell's onset, which is associated, on average, with the highest temperature deviation, largest day-to-day pressure drop, and greatest occurrence of oppressive air masses.
- While air temperature seems to be an appropriate tool for assessing heat-related mortality, it appears to be insufficient when effect of cold on CVD mortality is considered and thermal indices including the wind chill effect yield higher and probably more realistic cold-related mortality.
- While heat stress increases mortality especially due to chronic CVDs, the effects of cold stress are most pronounced on acute CVDs.
- A significant relationship was found within the most deprived regions between decreased socioeconomic status and increased heat-related mortality.

These results are potentially useful for better targeting biometeorological forecasts and warnings to population groups and regions especially vulnerable to heat and cold stress. Inasmuch as only a small percentage of the CVD mortality variance can be explained by models estimating weather–mortality relationships, regions with larger population counts –

rather than individual districts – need to be considered in order to achieve reasonable statistical power. Such urban agglomerations as Prague, Brno, Pilsen, cities in northwestern Bohemia, and the Ostrava agglomeration should be especially in focus, because urban areas are those most affected by heat stress due to urban heat island effects and large numbers of their inhabitants may live in neighbourhoods with lower socioeconomic status. Despite more significant and straightforward effects of heat on human health, cold effects on mortality and morbidity should not be neglected inasmuch as the wind chill effect may significantly heighten the degree of physiological stress, especially in rural highland areas. In contrast to mortality, insignificant excess hospital admissions for CVDs were observed on both hot and cold days. Such other health outcomes as emergency calls and hospital admissions for respiratory and heat/cold-related diseases should be considered in follow-up research evaluating the effects of extreme temperature events on public health in the Czech Republic. In addition, applicability and benefits of various biometeorological approaches for assessing heat and cold effects on public health need to be critically evaluated when criteria and algorithms for biometeorological forecasting and warning systems in the Czech Republic are defined or redeveloped.

1.9 References

Baccini M, Biggeri A, Accetta G, et al. (2008) Heat effects on mortality in 15 European cities. *Epidemiology* 19: 711–719. doi: 10.1097/EDE.0b013e318176bfcd.

Baccini M, Kosatsky T, Biggeri A (2013) Impact of summer heat on urban population mortality in Europe during the 1990s: An evaluation of years of life lost adjusted for harvesting. *PLoS ONE*, doi:10.1371/journal.pone.0069638.

Basu R (2009). High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environ Health* 8: 40. ISSN 1476-069X.

Balbus JM (2009). Identifying vulnerable subpopulations for climate change health effects in the United States. *J Occup Environ Med*, 51(1): 33–7.

Ballester J, Rodó X, Giorgi F (2010) Future changes in Central Europe heat waves expected to mostly follow summer mean warming. *Clim Dyn* 35: 1191–1205.

Barriopedro D, Fischer EM, Luterbacher J, et al. (2011) The hot summer of 2010: redrawing the temperature record map of Europe. *Science*, 332: 220–224.

Barnett AG, Tong S, Clements ACA (2010) What measure of temperature is the best predictor of mortality? *Environ Res* 110: 604–11. doi: 10.1016/j.envres.2010.05.006.

Bao J, Li X, Yu C (2015) The construction and validation of the heat vulnerability index, a review. *Int J Environ Res Public Health* 12: 7220–7234.

Becker S (2000) Bioclimatological rating of cities and resorts in South Africa according to the Climate Index. *Int J Climatol* 20: 1403–1414.

Bhaskaran K, Hajat S, Haines A, Herrett E, Wilkinson P, Smeeth L (2010) Short term effects of temperature on risk of myocardial infarction in England and Wales: time series regression analysis of the Myocardial Ischaemia National Audit Project (MINAP) registry. *BMJ* 341: c3823. doi: 10.1136/bmj.c3823

Bhaskaran K, Gasparrini A, Hajat S, et al. (2013) Time series regression studies in environmental epidemiology. *Int J Epidemiol* 42: 1187–95.

Błażejczyk, K, Epstein, Y, Jendritzky, G, Staiger, H, Tinz, B. (2012) Comparison of UTCI to selected thermal indices. *Int J Biometeorol* 56: 515–535.

Bobak M, Hertzman C, Skodova Z, Marmot M (1999) Socioeconomic status and cardiovascular risk factors in the Czech Republic. *Int J Epidemiol* 28: 46–52.

Bobb JF, Peng RD, Bell ML, Dominici F (2014) Heat-related mortality and adaptation to heat in the United States. *Environ Health Perspect* 122, 811–816.

Boeckmann M, Rohn I (2014) Is planned adaptation to heat reducing heat-related mortality and illness? A systematic review. *BMC Public Health*,.doi:10.1186/1471-2458-14-1112.

Bower D, Mcgregor GR, Hannah M, et al. (2007) Development of a spatial synoptic classification scheme for western Europe. *Int J Climatol* 27: 2017–2040.

Buckley JP, Samet JM, Richardson DB (2014) Commentary: Does air pollution confound studies of temperature? *Epidemiology* 25: 242–245.

Burkart K, Schneider A, Breitner S, et al. (2011) The effect of atmospheric thermal conditions and urban thermal pollution on all-cause and cardiovascular mortality in Bangladesh. *Environ Pollut* 159: 2035–43.

Burkart K, Canário P, Breitner S, et al. (2013) Interactive short-term effects of equivalent temperature and air pollution on human mortality in Berlin and Lisbon. *Environ Pollut* 183: 54–63.

Burkart K, Breitner S, Schneider A, et al. (2014) An analysis of heat effects in different subpopulations of Bangladesh. *Int J Biometeorol* 58: 227–37.

Burkart K, Meier F, Schneider A, et al. (2015) Modification of heat-related mortality in an elderly urban population by vegetation (Urban Green) and proximity to water (Urban Blue): Evidence from Lisbon, Portugal. *Environ Health Perspect*, doi:10.1289/ehp.1409529.

Cheng X, Su H (2010) Effects of climatic temperature stress on cardiovascular diseases. *Eur J Intern Med* 21: 164–167. doi: 10.1016/j.ejim.2010.03.001

Christidis N, Donaldson GC, Stott PA (2010) Causes for the recent changes in cold- and heat-related mortality in England and Wales. *Clim Change* 102: 539–553. doi: 10.1007/s10584-009-9774-0

Conlon KC, Rajkovich NB, White-Newsome JL, et al. (2011) Preventing cold-related morbidity and mortality in a changing climate. *Maturitas* 69: 197–202. doi: 10.1016/j.maturitas.2011.04.004

Curriero FC, Heiner KS, Samet JM et al (2002) Temperature and mortality in 11 cities of the eastern United States. *Am J Epidemiol* 155: 80–7.

Davis RE, Kalkstein LS (1990) Development of an automated spatial synoptic climatological classification. *Int J Climatol* 10: 769–794.

Davídkovová H, Plavcová E, Kynčl J, et al. (2014) Impacts of hot and cold spells differ for acute and chronic ischaemic heart diseases. *BMC Public Health* 14: 480.

Dragano N, Bobak M, Wege N et al (2007) Neighbourhood socioeconomic status and cardiovascular risk factors: a multilevel analysis of nine cities in the Czech Republic and Germany. *BMC Public Health* 7: 255. doi: 10.1186/1471-2458-7-255

Dzúrová D (1993) *Zdravotní stav obyvatel a kvalita životního prostředí: regionální souvislosti.* Ph.D. Thesis. Faculty of Science, Charles University, Prague, Czech Republic; p. 136 (in Czech).

Ebi KL (2014) Health in the new scenarios for climate change research. *Int J Environ Res Public Health* 11: 30–46. doi: 10.3390/ijerph110100030.

EEA – European Environment Agency (2010) Mapping the impacts of natural hazards and technological accidents in Europe: An overview of the last decade. Technical report No 13/2010. 144 pp. ISBN 978-92-9213-168-5.

Fanger PO (1972) *Thermal Comfort.* New York: McGraw- Hill.

Fiala D, Psikuta A, Jendritzky G, et al. (2010) Physiological modeling for technical, clinical and research applications. *Front Biosci* S2: 939–968.

Fouillet A, Rey G, Wagner V (2008) Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *Int J Epidemiol* 37: 309–17.

Gabriel KMA, Endlicher WR (2011) Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. *Environ Pollut* 159: 2044–2050. doi:10.1016/j.envpol.2011.01.016.

Gómez-Acebo I, Dierssen-Sotos T, Llorca J (2010) Effect of cold temperatures on mortality in Cantabria (Northern Spain): a case-crossover study. *Public Health* 124: 398–403. doi:10.1016/j.puhe.2010.03.025

Gosling SN, Lowe JA, McGregor GR, et al. (2009) Associations between elevated atmospheric temperature and human mortality: a critical review of literature. *Clim Change* 92(3–4): 299–341.

Gosling SN, McGregor GR, Lowe JA (2012) The benefits of quantifying climate model uncertainty in climate change impacts assessment: An example with heat-related mortality change estimates. *Clim Chang* 112: 217–231.

Gosling SN, McGregor GR, Páldy A (2007) Climate change and heat-related mortality in six cities part 1: model construction and validation. *Int J Biometeorol* 51: 525–40. doi: 10.1007/s00484-007-0092-9

Gosling SN, Warren R, Arnell NW et al (2011) A review of recent developments in climate change science. Part II: The global-scale impacts of climate change. *Prog Phys Geogr* 35: 443–464. doi: 10.1177/0309133311407650

Hajat S, Armstrong B, Baccini M, et al. (2006) Impact of high temperatures on mortality: is there an added heat wave effect? *Epidemiology* 17: 632–638.

Hajat S, Kovats RS, Lachowycz K (2007) Heat-related and cold-related deaths in England and Wales: who is at risk? *Occup Environ Med* 64: 93–100. doi: 10.1136/oem.2006.029017

Hattis D, Ogneva-Himmelberger Y, Ratick S (2012) The spatial variability of heat-related mortality in Massachusetts. *Appl Geogr* 33: 45–52. doi: 10.1016/j.apgeog.2011.07.008

Havenith G, Fiala D, Błazejczyk K, et al. (2012) The UTCI-clothing model. *Int J Biometeorol* 56: 461–70.

Hondula DM, Vanos JK, Gosling SN (2014) The SSC: a decade of climate-health research and future directions. *Int J Biometeorol*, 58: 109–120.

Höppe P (1984) Die Energiebilanz des Menschen. Wiss. Mitt. Meteorological Institute, University of München, Munchen.

Höppe P (1999) The physiological equivalent temperature, a universal index for the biometeorological assessment of the thermal environment. *Int J BiometeorolInt J Biometeorol*, 43: 71–5.

Huang C, Barnett, AG, Wang X, et al. (2011) Projecting future heat-related mortality under climate change scenarios: A systematic review. *Environ Health Perspect* 119: 1681–1690.

Huynen MMTE, Martens P, Schram D, et al. (2001) The impact of heat waves and cold spells on mortality rates in the Dutch population. *Environ Health Perspect* 109: 463–470. doi: 10.2307/3454704

IPCC (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jendritzky G, De Dear R, Havenith G (2012) UTCI–why another thermal index? *Int J Biometeorol*56: 421–8.

Jendritzky G, Nübler W (1981) A model analysing the urban thermal environment in physiologically significant terms. *Arch Met Geoph Biokl B* 29(4): 313–326.

Jendritzky G, Sönning W, Swantes HJ (1979) Ein objektives Bewertungsverfahren zur Beschreibung des thermischen Milieus in der Stadt- und Landschaftsplanung ("Klima-Michel-Modell"). *Beiträge Akad. Raumforschung Landesplanung* 28. Hannover.

Jendritzky G, Staiger H, Bucher K, et al. (2000) The Perceived Temperature: the method of the Deutscher Wetterdienst for the assessment of cold stress and heat load for the human body. Internet Workshop on Windchill, 03.–07. April 2000, hosted by the Meteorological Service of Canada

Kalkstein LS, Jamason PF, Greene JS, et al. (1996) The Philadelphia hot weather-health watch/warning system: development and application, summer 1995. *Bull Am Meteorol Soc* 77: 1519–1528.

Kántor N, Unger J (2011) The most problematic variable in the course of human-biometeorological comfort assessment — the mean radiant temperature. *Cent Eur J Geosci* 3: 90–100.

Kenney WL, Munce TA (2003) Invited review: aging and human temperature regulation. *J Appl Physiol* 95(6): 2598–603.

Kim Y-M, Kim S, Cheong H-K, et al. (2011) Comparison of temperature indexes for the impact assessment of heat stress on heat-related mortality. *Environ Health Toxicol* 26: e2011009.

Kinney PL, Schwartz J, Pascal M, et al. (2015) Winter season mortality: will climate warming bring benefits? *Environ Res Lett* 10: 064016.

Kirch W, Menne B, Bertollini R (2005) *Extreme Weather Events and Public Health Responses.* World Health Organization. Berlin, Springer. ISBN 3-540-24417-4.

Klein Rosenthal J, Kinney PL, Metzger KB (2014) Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006. *Health Place* 30: 45–60.

Kovach MM, Konrad CE II, Fuhrmann CM (2015) Area-level risk factors for heat-related illness in rural and urban locations across North Carolina, USA. *Appl Geogr* 60: 175–183.

Kyselý J (2002) Temporal fluctuations in heat waves at Prague-Klementinum, the Czech Republic, in 1901-1997, and their relationships to atmospheric circulation. *Int J Climatol* 22: 33-50

Kyselý J (2004) Mortality and displaced mortality during heat waves in the Czech Republic. *Int J Biometeorol* 49(2): 91–97.

Kyselý J (2008) Influence of the persistence of circulation patterns on warm and cold temperature anomalies in Europe: Analysis over the 20th century. *Glob Planet Change* 62: 147–163.

Kyselý J (2010) Recent severe heat waves in central Europe: how to view them in a long-term prospect? *Int J Climatol* 30: 89–109.

Kyselý J, Huth R (2004) Heat-related mortality in the Czech Republic examined through synoptic and 'traditional' approaches. *Clim Res* 25(3): 265–274.

Kyselý J, Plavcová E, Davídkovová H, et al. (2011) Comparison of hot and cold spell effects on cardiovascular mortality in individual population groups in the Czech Republic. *Clim Res* 49(2): 113–129.

Kyselý J, Plavcová E (2012) Declining impacts of hot spells on mortality in the Czech Republic, 1986–2009: adaptation to climate change? *Clim Change* 113: 437–453. doi: 10.1007/s10584-011-0358-4

Laschewski G, Jendritzky G (2002) Effects of the thermal environment on human health: an investigation of 30 years of daily mortality data from SW Germany. *Clim Res* 21:91–103. doi: 10.3354/cr021091

Lhotka O, Kyselý J (2015) Hot Central-European summer of 2013 in a long-term context. *IntJ Climatol*. doi: 10.1002/joc.4277

Ma W, Yang C, Chu C et al (2013) The impact of the 2008 cold spell on mortality in Shanghai, China. *Int J Biometeorol* 57: 179–84. doi: 10.1007/s00484-012-0545-7

Maier G, Grundstein A, Jang W, et al. (2014) Assessing the performance of a vulnerability index during oppressive heat across Georgia, United States. *Weather Clim Soc* 6: 253–263.

Matzarakis A, Rutz F, Mayer H (2007) Modelling radiation fluxes in simple and complex environments–application of the RayMan model. *Int J Biometeorol* 51: 323–34.

Matzarakis A, Muthers S, Koch E (2010) Human biometeorological evaluation of heat-related mortality in Vienna. *Theor Appl Climatol* 105: 1–10. doi: 10.1007/s00704-010-0372-x

McMichael AJ, Woodruff RE, Hales S (2006) Climate change and human health: present and future risks. *The Lancet* 367(9513): 859–869.

McMichael AJ, Wilkinson P, Kovats RS, et al. (2008) International study of temperature, heat and urban mortality: the 'ISOTHURM' project. *Int J Epidemiol* 37: 1121–1131.

McGregor GR (2011) Human biometeorology. *Prog in Phys Geogr* 36(1): 93–109. ISSN 1477-0296.

Morabito M, Crisci A, Messeri A et al (2014) Environmental Temperature and Thermal Indices : What Is the Most Effective Predictor of Heat-Related Mortality in Different Geographical Contexts ?*Scient World J* ID 961750. http://dx.doi.org/10.1155/2014/961750

Muthers S, Matzarakis A, Koch E (2010) Climate change and mortality in Vienna--a human biometeorological analysis based on regional climate modeling. *Int J Environ Res Public Health* 7: 2965–77.

Nastos PT, Matzarakis A (2011) The effect of air temperature and human thermal indices on mortality in Athens, Greece. *Theor Appl Climatol* 108: 591–599.

Oke TR (1982) The energetic basis of the urban heat island. *Q J R Meteorol Soc* 108: 1–24.

O'Neill MS, Carter R, Kish JK, et al. (2009) Preventing heat-related morbidity and mortality: new approaches in a changing climate. Maturitas, 64: 98–103.

Reid C.E, O'Neill MS, Gronlund CJ et al.. (2009) Mapping community determinants of heat vulnerability. *Environ Health Perspect* 117: 1730–1736.

Russo S, Dosio A, Sillmann J (2015) Top ten European heatwaves since 1950 and their occurrence in the future. *Environ Res Lett* 10: 124003. doi: 10.1088/1748-9326/10/12/124003

Saha MV, Davis, RE, Hondula DM (2014) Mortality displacement as a function of heat event strength in 7 US cities. *Am J Epidemiol* 179: 467–474.

Shitzer A, Tikuisis P (2012) Advances, shortcomings, and recommendations for wind chill estimation. *Int J Biometeorol* 56: 495–503

Sheridan SC (2002) The redevelopment of a weather-type classification scheme for North America. *Int J Climatol* 22: 51–68.

Sheridan SC, Kalkstein LS (2004) Progress in heat watch–warning system technology. *Bull Am Meteorol Soc* 85(12): 1931–1941.

Sheridan SC, Dolney TJ (2003) Heat, mortality, and level of urbanization: measuring vulnerability across Ohio, USA. *Clim Res* 24: 255–265

Staiger H, Laschewski G, Grätz A (2012) The perceived temperature - a versatile index for the assessment of the human thermal environment. Part A: scientific basics. *Int J Biometeorol* 56: 165–76. doi: 10.1007/s00484-011-0409-6

Steadman RG (1984) A universal scale of apparent temperature. *J Clim Appl Meteorol* 23: 1674–1687.

Tan J, Zheng Y, Tang X, et al. (2010) The urban heat island and its impact on heat waves and human health in Shanghai. *Int J Biometeorol* 54: 75–84 doi: 10.1007/s00484-009-0256-x

Toloo GS, Fitzgerald G, Aitken P, et al. (2013) Are heat warning systems effective? *Environ Health* 12: 27.

Uejio CK, Wilhelmi OV, Golden JS, et al. (2011) Intra-urban societal vulnerability to extreme heat: The role of heat exposure and the built environment, socioeconomics, and neighborhood stability. *Health Place* 17: 498–507.

Urban A, Davídkovová H, Kyselý J (2014) Heat- and cold-stress effects on cardiovascular mortality and morbidity among urban and rural populations in the Czech Republic. *Int J Biometeorol* 58: 1057–1068.

Urban A, Kyselý J (2014) Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic. *Int J Environ Res Public Health* 11: 952–67.

Urban A, Kyselý J (2015) Application of spatial synoptic classification in evaluating links between heat stress and cardiovascular mortality and morbidity in Prague, Czech Republic. *Int J Biometeorol* doi: 10.1007/s00484-015-1055-1

Urban A, Burkart K, Kyselý J, et al. (2016) Spatial patterns of heat-related cardiovascular mortality in the Czech Republic. *Int J Environ Res Public Health* 13: 284. doi: 10.3390/ijerph13030284

Vandentorren S, Suzan F, Medina S, et al. (2004) Mortality in 13 French cities during the August 2003 heat wave. *Am J Public Health* 94: 1518–20.

Vaneckova P, Neville G, Tippett V, et al. (2011) Do biometeorological indices improve modeling outcomes of heat-related mortality? *J Appl Meteorol Climatol* 50: 1165–1176.

von Klot S, Zanobetti A, Schwartz J (2012) Influenza epidemics, seasonality, and the effects of cold weather on cardiac mortality. *Environ Health* 11: 74.

Weihs P, Staiger H, Tinz B, et al. (2012) The uncertainty of UTCI due to uncertainties in the determination of radiation fluxes derived from measured and observed meteorological data. *Int J Biometeorol*, 56: 537–555.

Wood S (2006) *Generalized Additive Models: an introduction with R*. Chapman & Hall/CRC, London.

Wu W, Xiao Y, Li G, et al. (2013) Temperature-mortality relationship in four subtropical Chinsese cities: A time-series study using a distributed lag non-linear model. *Sci Total Environ* 449: 355-362

Wu PC, Lin CY, Lung SC, et al. (2010) Cardiovascular mortality during heat and cold events: determinants of regional vulnerability in Taiwan. *Occup Environ Med*, 68: 525–530 doi:10.1136/oem.2010.056168.

Xu Y, Dadvand P, Barrera-Gomez J, et al (2013) Differences on the effect of heat waves on mortality by sociodemographic and urban landscape characteristics. *J Epidemiol Community Health* 67: 519–525.

Zaninović K, Matzarakis A (2014) Impact of heat waves on mortality in Croatia. *Int J Biometeorol* 58: 1135–1145.

Zhang K, Rood RB, Michailidis G, et al. (2012) Comparing exposure metrics for classifying ‘dangerous heat’ in heat wave and health warning systems. *Environ Intern*. 46: 23–9. doi: 10.1016/j.envint.2012.05.001.

Yao R, Li B, Liu J (2009) A theoretical adaptive model of thermal comfort – adaptive Predicted Mean Vote (aPMV). *Building and Environment* 44: 2089–2096.

2 Heat- and cold-stress effects on cardiovascular mortality and morbidity among urban and rural populations in the Czech Republic

Aleš Urban [1,2], Hana Davídkovová [1,3,4], Jan Kyselý [1]

[1] *Institute of Atmospheric Physics AS CR, Boční II 1401, 141 31 Prague 4, Czech Republic*

[2] *Department of Physical Geography and Geoecology, Faculty of Science, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic*

[3] *Department of Physiology, Faculty of Science, Charles University, Czech Republic, Viničná 7, 128 44 Prague 2, Czech Republic*

[4] *Institute of Geophysics AS CR, Boční II 1401, 141 31 Prague 4, Czech Republic*

Abstract: Several studies have examined relationships of high and low air temperatures to cardiovascular mortality in the Czech Republic. Much less is understood about heat/cold-related cardiovascular morbidity and possible regional differences. This paper compares effects of warm and cold days on excess mortality and morbidity for cardiovascular diseases (CVDs) in the city of Prague and a rural region of southern Bohemia during 1994–2009. Population size and age structure are similar in the two regions. The results are evaluated for selected population groups (men and women). Excess mortality (number of deaths) and morbidity (number of hospital admissions) were determined as differences between observed and expected daily values, the latter being adjusted for long-term changes, annual and weekly cycles, and epidemics of influenza/acute respiratory infections.

Generally higher relative excess CVD mortality on warm days than on cold days was identified in both regions. In contrast to mortality, weak excess CVD morbidity was observed for both warm and cold days. Different responses of individual CVDs to heat versus cold stress may be caused by the different nature of each CVD and different physiological processes induced by heat or cold stress. The slight differences between Prague and southern Bohemia in response to heat versus cold stress suggest the possible influence of such environmental and socioeconomic factors as effects of urban heat island and exposure to air pollution, lifestyle differences, and divergence in population structure, which may result in differing vulnerability of urban versus rural population to temperature extremes.

Keywords: heat and cold stress, cardiovascular disease, mortality, morbidity, urban and rural differences, Central Europe

2.1 Introduction

Extreme temperature events, especially heat waves, have been documented as the most dangerous among all atmospheric hazards (at least in the mid-latitudes) and claim the largest numbers of victims (McMichael et al. 2006; Kyselý and Kříž 2008; Sheridan et al. 2008; Gosling et al. 2009; Gabriel and Endlicher 2011). An enormous number of fatalities, exceeding those from other natural hazards, occurred in Europe during extreme temperature episodes between 1998 and 2009 (EEA 2010). The extreme heat wave in 2003 caused more than 70,000 heat-related deaths in Europe, and similar estimates (55,000 fatalities) were reported for the 2010 heat wave in Russia by Barriopedro et al. (2011). Cold spells caused almost 1,900 excess deaths in Europe during 1998–2009 according to estimates of EEA (2010), but some recent studies suggest that cold-related mortality may even be substantially underestimated if lagged effects are not taken into account, and its overall magnitude may be comparable to that of heat-related mortality (Kyselý et al. 2011). Due to the rise in global mean temperature, extreme heat events are expected to increase in the 21st century, and, conversely, frequency of extreme cold events is projected to decrease (IPCC 2007; Gosling et al. 2009). In central Europe specifically, approximately 40% of July and August days at the end of the 21st century are projected to be extreme with respect to current climatic conditions (Ballester et al. 2009). Decreased cold-related mortality and increased heat-related mortality are expected in a future climate, but there is inconsistency among individual studies as to the magnitude of those changes (Gosling et al. 2009). Moreover, the role of adaptation in modifying climate–mortality relationships is another major uncertainty (O'Neill et al. 2009; Christidis et al. 2010; Conlon et al. 2011; Kyselý and Plavcová 2012).

Effects of heat and cold stress on increased mortality have been demonstrated mainly for cardiovascular and respiratory diseases (e.g. Huynen et al. 2001; Basu and Samet 2002; Braga et al. 2002; Cheng and Su 2010). While during heat waves excess mortality often occurs for several days which are then followed by decrease of mortality rates to below expected levels (so-called mortality displacement; Gosling et al. 2009), the effect of cold spells is more lagged and mortality may exceed expected values for several weeks while showing no subsequent decrease below expected levels (Huynen et al. 2001; Laschewski and Jendritzky 2002; Cheng and Su 2010).

The relationship between extreme temperature (which is often used as a simple proxy for ambient thermal environment) and excess morbidity (hospital admissions) has been found to be much less consistent than in the case of mortality, and the range of affected diseases is more diverse (Ye et al. 2012). Increased morbidity during heat waves has been observed for example in Italy (Mastrangelo et al. 2007), Great Britain (Kovats et al. 2004), and the United States (Semenza et al. 1999; Knowlton et al. 2009). Although morbidity due to cardiovascular diseases (CVDs), as the primary discharge diagnosis, did not increase significantly in most cases, the presence of a chronic CVD as a preexisting condition has been demonstrated as an important risk factor for hospital admission (Semenza et al. 1999). Several studies have examined the effects of extreme low temperatures on CVD morbidity (e.g. Schwartz et al. 2004; Morabito et al. 2005; Bayentin et al. 2010; Ma et al. 2011) and reported contradictory findings. Moreover, those studies have not taken into account effects of influenza and acute respiratory infections, which comprise a major factor influencing CVD mortality in winter season (Kynčl et al. 2005; Cheng and Su 2010).

The aims of this paper are to complement previous studies on heat-related (Kyselý and Huth 2004; Kyselý and Kříž 2008) and cold-related (Kyselý et al. 2009 2011) mortality in the Czech Republic in two main directions: (1) to compare the short-term effects of heat and cold stress on CVD mortality and morbidity, and (2) to examine differences in these effects between an urban and a rural region. Such extension of previous work was made possible by completion and release of datasets with *individual* records of deaths and hospital admissions due to CVD, whereas all previous studies had been based on *aggregate* daily numbers of deaths for the entire population of the Czech Republic and all CVDs together. Hence, the earlier work had not allowed for examining regional differences, differences between mortality and morbidity, or differences regarding individual types of disorders.

2.2 Area of investigation, data, and methods

2.2.1 Population under study

The two regions under study are the city of Prague and the rural region of southern Bohemia, each with a population of about 1.2 million inhabitants (see Figure 2.1 for detail). The city of Prague is by far the largest city in the Czech Republic and represents the urban population in this study. For comparison, we decided to consider a rural region with a similar number of inhabitants but low proportion of urban population. OECD's international terminology (Spiezia 2003) defines a rural region as one in which at least 37.5% of inhabitants live in municipalities with population density less than 150 inhabitants per 1 km^2. In accordance with this definition, the two regional administrative units in the Czech Republic with the largest proportions of rural population are the South Bohemia Region (*Jihočeský kraj*, 46.8%) and the adjoining Highlands Region (*Kraj Vysočina*, 51.9%; Blatecká 2006). Together, these constitute a geographic region with population size and structure similar to Prague (Figure 2.1), but only 36% of inhabitants there live in municipalities with population above 10,000 (CZSO 2012). The results of a study by Vobecká (2009), who examined spatial differentiation of population on the bases of commuting accessibility of regional centers in the Czech Republic, also support the selection of these two adjoining districts as a single rural region (hereafter termed *southern Bohemia*) for the purpose of this study.

Population groups	Prague		Southern Bohemia	
Total	1,249,026	[%]	1,152,635	[%]
Men	608,316	49	570,035	49
Women	640,710	51	582,600	51
Average age [yrs]	41.6		40.6	

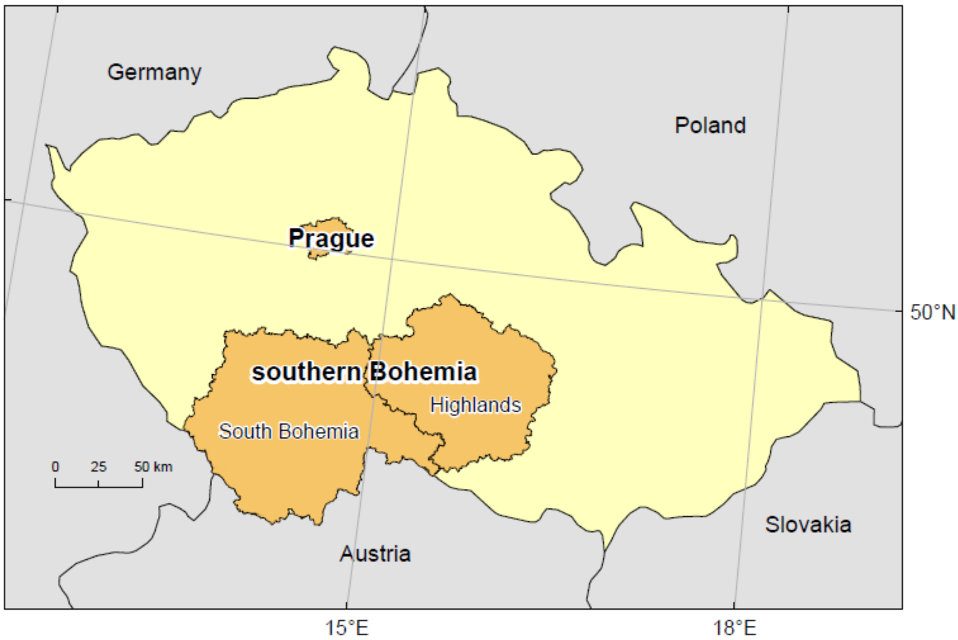

Figure 2.1 Location of the examined regions (Prague and southern Bohemia) in the Czech Republic. Basic demographic characteristics of the two regions are also presented.

2.2.2 Mortality and morbidity data

Daily data on mortality due to CVDs (codes I00–I99 according to the International Statistical Classification of Diseases, 10th Revision [ICD–10]; Table 2.1) and on hospital admissions due to CVDs were obtained from the Czech Statistical Office (CZSO) and the Institute of Health Information and Statistics (IHIS). The data cover the period of 1994–2009. The data records include the primary cause of each death or hospital admission and the region of residence for each decedent or patient. The records were stratified by gender.

To account for long-term changes in mortality/morbidity (related to demographic, health care and life-style changes) as well as short-term variations due to the annual cycle and weekly cycles, the daily numbers of deaths/hospital admissions must be standardized. We employed an indirect standardization procedure analogous to that used by Whitman et al. (1997), Smoyer et al. (2000) and Kyselý (2004), in which a series of daily excess mortality/morbidity was established by calculating deviations of the observed and expected (baseline) mortality/morbidity for each day of the examined period.

The expected number of deaths/hospital admissions $M_0(y,d)$ for year *y* (*y* = 1994, ... 2009) and day *d* (*d* = 1, ... 365) was determined according to the formula

$$M_0(y,d) = M_0(d).W(y,d).Y(y)\ .$$

In the equation, $M_0(d)$ denotes the mean daily mortality/morbidity on day *d* in a year (computed from the mean annual cycle over 1994–2009). Because Kynčl et al. (2005) and Kyselý et al. (2009) found relationships between influenza/acute respiratory infections (ARI) and mortality to be significant and strongest with the 7-day lag, all days corresponding to the epidemics of influenza/ARI, with the 7-day lag, were removed from the mortality/morbidity dataset before calculation of the mean annual cycle. $W(y,d)$ is a correction factor for the observed weekly cycle of mortality/morbidity, calculated separately for individual days of the week and defined as the ratio of the mean mortality/morbidity on a given day to the overall mean mortality/morbidity. $Y(y)$ is a correction factor for the observed year-to-year changes in mortality/morbidity, defined as the ratio of the number of deaths/hospital admissions in year *y* to the mean annual number of deaths/hospital admissions during the analyzed period. The correction factors for the weekly cycle $W(y,d)$ and the year-to-year changes $Y(y)$ were calculated over the April–November period when the effects of epidemics of influenza/acute respiratory infections in the data are negligible. In calculating $W(y,d)$, all public holidays were excluded.

In morbidity data, outliers related to recording errors (2 days in Prague: 1 January 1994, 1 July 1997; and 1 day in southern Bohemia: 1 July 2001) were removed from the database before calculating the mean annual cycle $M_0(d)$ and the correction factors for the weekly cycle $W(y,d)$. Consultations with representatives of health insurance companies revealed that these dates probably represented errors relating to changes in the method of reporting patient payments for health insurance. The corresponding days were omitted from the analysis, together with all days on which hospital admissions might have been affected by influenza/acute respiratory infection epidemics (169 winter days during 6 epidemics in both regions).

Table 2.1 Examined diagnoses according to the International Statistical Classification of Diseases (ICD–10) coding and abbreviations used.

ICD–10 code	Abbreviation	Diagnosis
I00–I99	CVD	cardiovascular disease
I20–I25	IHD	ischemic heart disease
I60–I69	CD	cerebrovascular disease
I21–I22	MI	myocardial infarction (acute and subsequent)
I25	CIHD	chronic ischemic heart disease
I70	ASVD	atherosclerosis – atherosclerotic vascular disease
I80	P&TP	phlebitis and thrombophlebitis

Mortality from CVDs comprises more than 50% of total mortality in the Czech Republic (CZSO 2012). Among CVDs, ischemic heart disease (IHD, 43.0% of CVD deaths) and cerebrovascular disease (CD, 27.8%) form the two main groups, responsible for more than 70% of all CVD deaths (Table 2.2). We analyze also individual diseases that make up the largest share in cardiovascular mortality within the Czech population: myocardial infarction (MI, 17.0% of CVD deaths), chronic IHD (25.3%) and atherosclerosis (16.7%). Detailed statistics for the two regions are presented in Table 2.2. The percentage of death certificates based on autopsy is relatively high in the Czech Republic and comparable with that in western European countries, and it changed little over the study period (from 34% in 1994 to 29% in 2009; IHIS 2010). Due to very low mortality from phlebitis and thrombophlebitis (0.5% of all CVDs, Table 2.2), only morbidity was analyzed in their case.

Table 2.2 Regional statistics for morbidity (number of hospital admissions) and mortality (number of deaths) in two examined regions during 1994–2009 and shares in CVD morbidity and mortality (%).

	Prague				Southern Bohemia			
Diagnosis	Morbidity		Mortality		Morbidity		Mortality	
CVD	598,134	[%]	110,708	[%]	576,484	[%]	100,838	[%]
IHD	211,933	35.4	44,624	40.3	168,976	29.3	47,033	46.6
CD	110,705	18.5	28,045	25.3	97,207	16.9	28,056	27.8
MI	33,981	5.7	15,205	13.7	39,720	6.9	19,582	19.4
CIHD	147,171	24.6	28,956	26.2	80,110	13.9	26,974	26.7
ASVD	59,455	9.9	23,410	21.1	42,860	7.4	13,137	13.0
P&TP	16,769	2.8	538	0.5	22,706	3.9	549	0.5

2.2.3 Meteorological data

Although many meteorological variables have been used to study effects of heat and cold stress on mortality/morbidity, it remains uncertain which measure is best (Gosling et al. 2009; Ye et al. 2012). Moreover, the relationship of apparent temperature (heat index) or other indices to mortality is often reported to be similar to, or even weaker than, that between air temperature and mortality (Kyselý 2004; Carder et al. 2005; Gosling et al. 2009). Vaneckova et al. (2011) demonstrated there to be no significant difference in the performance of simple average air temperature and biometeorological indices in analyzing heat-related mortality. Thus, we use average daily air temperature as the sole meteorological variable in this study.

Use of air temperature allows for employing a dataset covering the two selected regions in a high-resolution regular grid (such data are not available for other meteorological variables needed as inputs for calculating heat index or other indices). The gridded dataset is based on interpolating mean daily air temperature from irregularly spaced meteorological stations operated by the Czech Hydrometeorological Institute (the GriSt dataset described in Kyselý and Plavcová 2010). The average daily temperature for each region was calculated from grid boxes 25 × 25 km covering the two regions. The empirical distributions of average daily temperature are similar in the two regions, except that the whole distribution is shifted by about 2 °C to higher temperatures in Prague in both seasons (Table 2.3). Days with average temperature above/below the 90%/10% quantile of the empirical distribution in summer (June, July, August) and winter (December, January, February) seasons over 1994–2009 were defined as *warm/cold* days. Use of the percentile method (unlike determining the exact temperature threshold) allows for examining approximately the same number of cases in different regions and at both temperature extremes. This method has commonly been used for regional comparison of heat/cold impact on human health (e.g. Hajat et al. 2007; Medina-Ramón and Schwartz 2007; Gómez-Acebo et al. 2010; Gabriel and Endlicher 2011).

Table 2.3 Statistics of winter and summer mean daily temperature for 1994–2009 in the two regions. The average altitudes were estimated using ArcGIS software by analyzing contour lines from digital geographical database ArcČR 500 (provided by ARCDATA).

Prague (270 m a.s.l.)			
Winter	**°C**	**Summer**	**°C**
Average	0.6	Average	18.8
Standard deviation	4.8	Standard deviation	3.6
Minimum	−17.3	Minimum	8.6
Maximum	13.5	Maximum	29.2
10% quantile	−5.7	90% quantile	23.4

Southern Bohemia (580 m a.s.l.)			
Winter	**°C**	**Summer**	**°C**
Average	−1.3	Average	16.8
Standard deviation	4.7	Standard deviation	3.5
Minimum	−18.7	Minimum	6.1
Maximum	10.7	Maximum	26.2
10% quantile	−7.6	90% quantile	21.2

As mentioned above, the number of warm and cold days is the same in the two regions, apart from rounding effects in temperature data. However, as some winter days were omitted from the analysis due to epidemics of influenza/ARI (see section Mortality and morbidity data), and also because winter seasons (90 or 91 days) are shorter than summer seasons (92 days), the examined sample of cold days (127 days) is slightly smaller than that of warm days (148 days) in each region.

Deviations of mortality and morbidity from the expected values on warm/cold days (D_0) and one day thereafter (D_{+1}, to capture basic lagged effects) were summed and averaged over all warm/cold days. In the case of consecutive warm/cold days, only D_0 values were included into the calculation. Statistical significance of the mean deviations for warm/cold days was evaluated by the 95% confidence interval (CI), calculated using the lower and upper limit factors for a Poisson-distributed variable according to Schoenberg (1983); for the number of cases larger than 100, the normal approximation was used.

2.3 Results

2.3.1 Mortality

On warm days, we found significant (p = 0.05) excess mortality from all examined groups of diagnoses as well as individual CVDs other than MI in both regions (Table 2.4, Figure 2.2). Consistently for all diagnoses, higher anomalies were found in Prague than in southern Bohemia, with the largest difference for atherosclerosis (mean excess mortality 21% in Prague but 12% in southern Bohemia).

Table 4 shows mean excess mortality on warm days also for individual genders. In both regions and for all groups of diagnoses as well as for individual CVDs except for atherosclerosis, excess mortality was greater in females than males. While in the rural region of southern Bohemia excess mortality was not significant in males for any CVD, in Prague it was significant also in males for all CVDs together, chronic IHD and atherosclerosis. In females, on the other hand, excess mortality was, in both regions, significant for all groups of diagnoses other than MI (and atherosclerosis in southern Bohemia; Table 2.4).

The largest heat-related effects on CVD mortality in both males and females were found for atherosclerosis in the population of Prague (23% and 20%, respectively) while the smallest were for MI (in both regions). This notable and somewhat counterintuitive finding is examined further in the Discussion section.

Table 2.4 Relative excess cardiovascular mortality with 95% confidence intervals (in parentheses) on warm days (10% warmest days in summer) in Prague and southern Bohemia during 1994–2009. Values significantly different from zero are in bold.

	Prague		
Gender **Diagnosis**	**Male**	**Female**	**Male and female**
all CVD	**10.0 (5.0;15.1)**	**12.5 (8.1;17.0)**	**11.4 (8.1;14.8)**
IHD	4.0 (−2.9; 11.5)	**11.7 (4.6; 19.2)**	**7.9 (2.9; 13.1)**
CD	7.3 (−2.8; 18.5)	**11.2 (3.3; 19.7)**	**9.8 (3.5; 16.4)**
MI	−4.8 (−15.4; 7.1)	1.5 (−10.5; 15.2)	−1.9 (−10.0; 6.9)
CIHD	**9.5 (0.5; 19.4)**	**14.8 (6.2; 24.1)**	**12.4 (6.1; 19.0)**
ASVD	**22.7 (10.1; 36.8)**	**20.4 (10.5; 31.2)**	**21.3 (13.4; 29.7)**

	Southern Bohemia		
Gender **Diagnosis**	**Male**	**Female**	**Male and female**
all CVD	4.4 (−0.6; 9.6)	**11.7 (7.0; 16.6)**	**8.3 (4.9; 11.9)**
IHD	1.1 (−5.6; 8.2)	**14.1 (6.9; 21.8)**	**7.4 (2.5; 12.6)**
CD	5.6 (−4.4; 16.6)	**10.1 (1.8; 19.0)**	**8.3 (1.9; 15.1)**
MI	1.0 (−8.4; 11.3)	4.6 (−7.1; 17.6)	2.4 (−11.8; 18.9)
CIHD	0.7 (−8.6; 10.9)	**19.6 (10.5; 29.4)**	**11.2 (4.6; 18.2)**
ASVD	12.8 (−2.2; 30.1)	11.9 (−0.3; 25.6)	**12.3 (2.7; 22.8)**

Table 2.5 Relative excess cardiovascular mortality together with 95% confidence intervals (in parentheses) on cold days (10% coldest days in winter) in Prague and southern Bohemia during 1994–2009. Values significantly different from zero are in bold.

	Prague		
Gender **Diagnosis**	**Male**	**Female**	**Male and female**
all CVD	2.4 (−2.7; 7.7)	0.9 (−3.4; 5.4)	1.5 (−1.8; 4.9)
IHD	7.0 (−0.8; 15.3)	−3.5 (−10.5; 4.0)	1.5 (−3.8; 7.0)
CD	−6.6 (−16.6; 4.7)	7.7 (−0.7; 16.9)	2.4 (−4.1; 9.4)
MI	6.3 (−6.0; 20.2)	1.8 (−11.2; 16.7)	4.2 (−4.8; 14.2)
CIHD	7.9 (−2.0; 18.8)	−6.4 (−14.6; 2.6)	−0.1 (−6.5; 6.8)
ASVD	1.7 (−9.3; 14.1)	3.5 (−5.1; 12.9)	2.9 (−4.0; 10.2)

	Southern Bohemia		
Gender **Diagnosis**	**Male**	**Female**	**Male and female**
all CVD	4.3 (−0.9; 9.7)	0.8 (−3.8; 5.6)	2.4 (−1.1; 5.9)
IHD	0.5 (−6.5; 10.4)	5.3 (−2.0; 13.0)	2.9 (−2.2; 8.3)
CD	7.2 (−3.0; 18.5)	0.9 (−7.2; 9.7)	3.4 (−3.0; 10.3)
MI	**12.4 (1.9; 24.0)**	11.0 (−1.9; 25.5)	**11.9 (3.6; 20.8)**
CIHD	−10.3 (−19.7; 0.1)	1.3 (−7.3; 10.6)	−3.6 (−10.0; 3.2)
ASVD	14.2 (−1.6; 32.5)	−7.5 (−18.9; 5.5)	1.0 (−8.5; 11.4)

Only few statistically significant values of excess mortality were found on cold days, as shown in Table 2.5. In the population as a whole, only MI in southern Bohemia exceeded significantly the expected level. In Prague, the mean excess mortality for MI – although not significant – was also the highest among all CVDs. The mean excess mortality was on average much smaller on cold days than warm days, but there is a pattern of consistently (in both regions) positive values of mean excess mortality for all CVDs except chronic IHD. All groups of diagnoses except for chronic IHD also reached (in the population as a whole) higher cold-related mortality in southern Bohemia than in Prague.

Table 2.5 shows that the relatively large and significant effect of cold days on mortality from MI in southern Bohemia is due to excess mortality in both males and females, although only in males was the effect significant.

An overall comparison of mortality anomalies on warm and cold days in the urban and rural region is illustrated in Figure 2.2. To summarize, the main findings are that (i) the short-term effects of warm days are larger and much more often significant than those of cold days for most diagnoses; (ii) the excess mortality on warm days tends to be greater in Prague while it is greater on cold days in southern Bohemia; and (iii) the CVD diagnoses that behave differently as to heat and cold effects are mainly heat-related chronic IHD and atherosclerosis, as well as cold-related MI.

2.3.2 Hospital admissions

When all CVDs were considered together, we found no significant heat or cold effects on hospital admissions in any region, either in the whole population or in females and males analyzed separately. The same conclusion holds true for the two main groups of CVDs (IHD and CD). When individual CVDs were examined, only 2 statistically significant situations were found: In the population as a whole, hospital admissions for phlebitis and thrombophlebitis in Prague reached significant excess anomaly (9.2% [95% CI: 0.3% to 18.8%]) on cold days (Figure 2.3). In individual population groups, significant excess morbidity was found in atherosclerosis among women on warm days in Prague (6.4% [95% CI: 0.4% to 12.8%]). Inasmuch as the lower bound of the 95% CI is very close to zero in both cases, however, these findings should be interpreted with caution. The few (weakly) significant findings are likely a random effect due to the multiple comparisons of individual diagnoses and population groups, as they are found only in 2 out of 72 tests performed.

2.4 Discussion

2.4.1 Differences in mortality and morbidity

Significant excess CVD mortality on warm and cold days, including regional differences between the city of Prague and the rural region of southern Bohemia, were found in this study. In contrast to mortality, a weak impact of warm and cold days on excess morbidity (hospital admissions) due to CVDs was observed (cf. Figures 2.2 and 2.3). Significant excess morbidity was found only for chronic CVDs in two population groups. With respect to the number of tested diagnoses and population groups, one has to be very careful when interpreting the few significant results for morbidity.

The absence of excess hospital admissions (on days D_0 and D_{+1} during and after a warm/cold day) is a somewhat counterintuitive finding and may have several causes. The first possible explanation is that it may be caused by longer delay in hospitalizations (Bhaskaran et al. 2010). The delay in seeking medical care and hospital admission can be up to a week from the first onset of symptoms (Gravely-Witte et al. 2010). While lagged cold effect on mortality up to two weeks has been found in a number of studies (Carder 2005; Hajat et al. 2007; Kyselý et al. 2011), results of studies that examined lagged cold effect on hospital admissions are inconsistent (Schwartz et al. 2004; Morabito et al. 2005; Morabito et al. 2006; Bayentin et al. 2010; Bhaskharan et al. 2010). Moreover, as mentioned in the Introduction, most of the cited studies did not take into account influenza epidemics (only Bhaskharan et al. 2010). We also looked at possible lagged effects of cold days on hospital admissions but found no signature of significant excess CVD morbidity for longer lags (up to 14 days) in our data. Nevertheless, since the explanation of the lagged cold effect on mortality, and even more on morbidity, remains uncertain (Schwartz 2004; Carder 2005; Morabito et al. 2006; Ye et al. 2012), more detailed analysis of the lagged effect was not the main focus of this study.

Second, although Schwartz et al. (2004) had observed relatively quick increase of MI hospital admissions during high temperatures, we found no significant anomaly of morbidity for such acute CVDs as MI or CD on either warm or cold days. This may be because an appreciable number of people die from acute CVDs before they can be admitted to hospital (Kovats et al. 2004; Linares and Díaz 2008). A third reason for not finding significant temperature-related CVD morbidity may be that there was another stated primary cause of hospital admission (heat stroke, dehydration), even though chronic CVDs (such as atherosclerosis, hypertensive disease, and other heart diseases) were frequently the underlying cause of admissions during a heat wave (Semenza et al. 1999). Knowlton et al. (2009) observed a significant increase in emergency department visits with CVDs during heat waves, while the excess of hospitalizations for CVDs was not significant. Representing more acute but less severe incidents, emergency visits can capture the effect of extreme temperature exposure at an earlier stage than do hospitalizations (Ye et al. 2012).

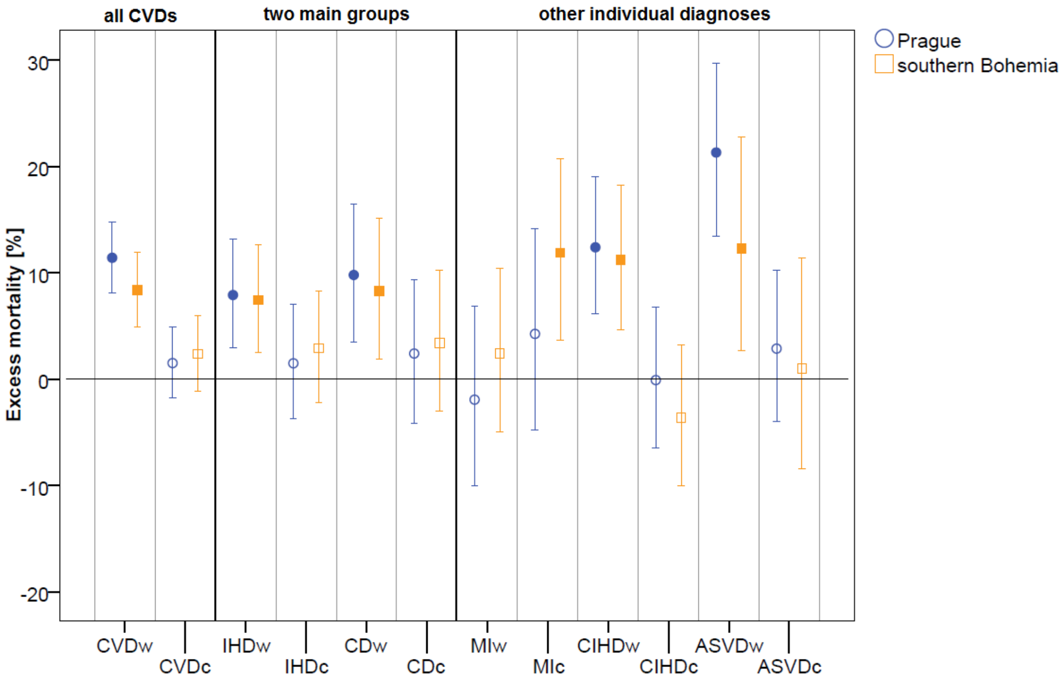

Figure 2.2 Relative excess mortality (%) for individual CVDs and the population as a whole on (w) warm and (c) cold days in Prague and southern Bohemia during 1994–2009. See Table 1 for definition of abbreviations. *Filled markers* indicate positive values significant at $p = 0.05$. *Error bars* indicate 95% confidence intervals.

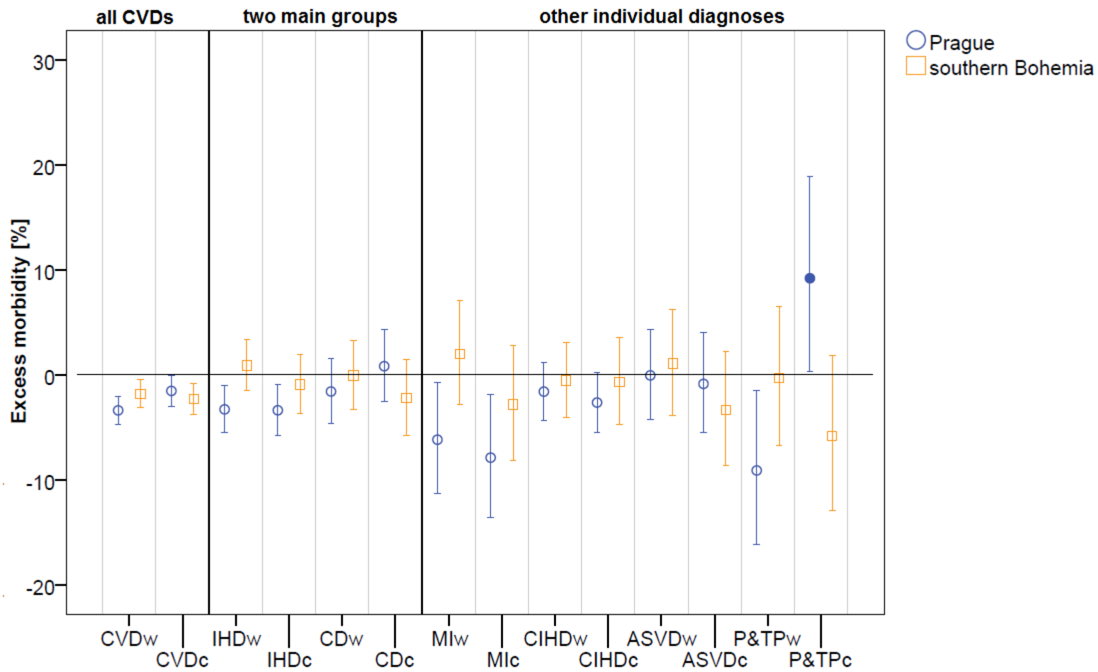

Figure 2.3 Relative excess morbidity (%) for individual CVDs and the population as a whole on (w) warm and (c) cold days in Prague and southern Bohemia during 1994–2009. See Table 1 for definition of abbreviations. *Filled markers* indicate positive values significant at $p = 0.05$. *Error bars* indicate 95% confidence intervals. Range of the y-axis is the same as in Figure 2.2.

2.4.2 Urban and rural differences

A more pronounced effect of warm days was found in Prague while stronger cold effect was seen in southern Bohemia (see Figures 2.2 and 2.3). Although these are expected findings, this study presents the first attempt to quantify the differences between an urban and a rural population in the Czech Republic, and it shows that heat stress has a significant impact also on rural population. The urban–rural differences in mortality impacts may be caused by different urban and rural environmental and socioeconomic conditions, as discussed below.

Environmental factors

The number of studies for European populations to which the present findings may be compared is limited. Gabriel and Endlicher (2011) revealed mortality risks in both urban and rural areas at Berlin and Brandenburg during heat waves, while the highest mortality rates were in the most densely built-up districts within the city of Berlin. In England and Wales, strongest heat effects on mortality were found in London in contrast to the strongest cold effects occurring in the East of England region, which may be attributed in part to a relatively older population and its exposure to cold winds in this region (Hajat et al. 2007). However, the estimate of the cold effect in the East region was much reduced after including years with missing air pollution data into the analysis. Other studies have found generally greater vulnerability of the rural population to cold stress (Gómez-Acebo et al. 2010; Conlon et al. 2011) and, by contrast, higher risk of mortality due to extremely high air temperatures among the urban population (O'Neill et al. 2009; Tan et al. 2010) and in densely urbanized neighborhoods (Smoyer et al. 2000; Medina-Ramón and Schwartz 2007; Loughnan et al. 2008). Enhanced urban heat island effect at night, which prevents sufficient air cooling in urban areas during heat waves (Mills 2004; Kovats and Hajat 2008; Fischer et al. 2012), has often been mentioned as the main reason for differences in the magnitude of urban and rural heat stress. The average temperature in Prague is 2 °C higher in comparison with that in southern Bohemia, and the values of temperature percentiles determining warm and cold days are also about 2 °C higher in Prague (cf. Table 2.3). The lower average altitude and urban heat island effect (Beranová and Huth 2005) are possible reasons for the differences. These factors can diminish the cold stress and heighten the heat effect on human health in urban conditions for the city of Prague. This also suggests that the CVD mortality response is related more to absolute threshold temperature than to relative thresholds in percentiles.

Moreover, in addition to the air temperature and other meteorological variables modified by altered water and energy balance of the urban heat island (Holmer and Eliasson 1999; Arnfield 2003; Kuttler et al. 2007; Mills 2007; Trusilova et al. 2008; Fischer et al. 2012), air pollution has a considerable impact on human health. Especially high concentrations of particulate matter (PM), NO_x, CO and O_3 have been reported to have adverse effect on patients with CVDs (Maitre et al. 2006). A study in Germany found that air quality was mostly determined by the level of PM_{10} concentration (Junk et al. 2003). Long-term exposure to ambient PM, in particular, can considerably accelerate the development of atherosclerosis and other chronic diseases of the veins and heart (Brook et al. 2004; Chen and Goldberg 2009; Kaufman 2010; Chuang et al. 2011). Short-term changes in the concentration of air pollution may also heighten the risk of a cardiovascular event (Brook et al. 2004). Short-term pollution changes are influenced by weather conditions, however, and in several studies cardiovascular events were found to be linked more significantly with extreme temperature than air pollution (Keatinge and Donaldson 2001; Basu and Samet 2002; Filleul et al. 2006; Vaneckova et al. 2011).

Long-term exposure to air pollution may be the cause of the particularly high heat-related mortality from atherosclerosis in Prague (+21% excess deaths on warm days). The urban heat island effect and faster atherosclerosis development due to the long-term exposure to air pollution might be important factors contributing to the regional differences in heat-related mortality.

Socioeconomic factors

Some studies in the U.S. have not found higher proportions of heat-related deaths in urban vs. rural areas (e.g., Sheridan and Dolney 2003 in Ohio; Hattis et al. 2012 in Massachusetts). In the Massachusetts study, Hattis et al. (2012) found the highest rate of heat-related mortality in the most populated areas, but significant influence of demographic characteristics (such as age composition and representation of African-American ethnicity) on mortality rate was a more important factor than the rate of urbanization itself. Moreover, heat-related mortality in U.S. cities is probably reduced by the protective effect of air conditioning (Medina-Ramón and Schwartz 2007) which, particularly in cities (Sheridan and Dolney 2003), is much more widespread in American households than in Europe (Henderson 2005). Many other socioeconomic factors, such as lifestyle differences, occupation, economic status, and quality of health care (Clark et al. 2007), may contribute to the differences in mortality under urban vs. rural conditions. In addition to the reduced cold stress in winter due to the warming effect of the urban heat island, the lower vulnerability of the Prague population to low temperatures can be attributed to the different lifestyle (less time spent outdoors, especially among pensioners; Aylin et al. 2001; Rudge and Gilchrist 2005). More pronounced cold effect and differences in regimen (such as diet and smoking, which may in turn be associated with such other factors as education and economic status; Bobak et al., 1999) might be the reason for generally higher cold-related mortality for MI in the population of southern Bohemia (Tanis 2003; Bayentin et al. 2010).

The excess deaths associated with direct exposure to cold may partly be those of homeless people, who are particularly vulnerable to cold. The numbers of homeless people were formerly relatively small in the Czech Republic compared to western European countries, but their numbers began to increase towards the end of the examined period (Kyselý et al. 2011). In the Czech Republic, homeless people are concentrated especially in the city of Prague. In 2004, it is estimated that about 3,000 homeless people (86% of whom were men and 72% in the age group of 25–60 years; Mikeszová 2010) lived there. Estimates as to the numbers of homeless people are much smaller in other Czech cities. Statistics for deaths of homeless people in the Czech population are incomplete and available only from 2000. During 2000–2007, these include 40 reported deaths of homeless persons in Prague and 3 in southern Bohemia, among which CVDs were the primary cause of death in 28 and 1 cases, respectively. However, none of these occurred on cold days in either Prague or southern Bohemia over the 8-year period for which the data are available. This suggests that deaths of homeless people do not significantly affect our results for CVD mortality.

2.4.3 Differences among individual CVDs

The results revealed differences in warm and cold effect on individual CVDs that deserve further investigation. Figure 2.2 shows higher vulnerability to chronic CVDs such as atherosclerosis and chronic IHD on warm days and, by contrast, higher risk of death from myocardial infarction (MI) on cold days. These differences may be interpreted as consequences of different physiological processes on the circulatory system due to heat vs. cold stress.

Exposure to heat could increase platelet and red blood cell count, blood viscosity, serum cholesterol levels and cardiac output, thus leading to dehydration, hypotension and endothelial cell damage (Cheng and Su 2010). Therefore, high temperature might aggravate coronary or peripheral arterial illness. Dehydration, overheating and exhaustion, especially among (older) people with reduced thermoregulation ability due to chronic diseases (such as atherosclerosis) can lead to increased heat-related hospital admissions (Semenza et al. 1999) or to heat-related deaths (Basu and Samet 2002; Mercer 2002) from atherosclerosis or chronic IHD, as observed in both regions.

Cold stress is associated with increased blood pressure and platelet aggregation; heightened vasoconstriction; increased blood viscosity and levels of red blood cell count, plasma cholesterol and plasma fibrinogen; and greater hemoconcentration, all of which could contribute to thrombosis (The Eurowinter Group 1997; Cheng and Su 2010; Abrignani et al. 2011). Physical activity during cold weather can bring a clot to the heart and cause myocardial infarction (Schwartz et al. 2004). These mechanisms may be possible reasons for significant excess mortality due to MI on cold days.

In cases of cerebral or coronary atherosclerosis, increased physical stress caused by heat- as well as cold-related increase in blood pressure and vasoconstriction may lead to cerebral or myocardial infarction (Cheng and Su 2010). Various types of stroke are influenced by the diversity of aforementioned physiological mechanisms and can increase heat- as well as cold-related stroke mortality and morbidity (Feigin et al. 2000; Kyobutungi et al. 2005; Dawson et al. 2008; Wang et al. 2009; Green et al. 2010). In our study, however, CD mortality increased significantly ($p = 0.05$) only on warm days and in both regions.

2.5 Conclusions

The present study evaluated for the first time two sorts of differences in heat and cold stress effects on a central European population, namely differences between an urban (Prague) and a rural (southern Bohemia) region, as well as between CVD mortality and morbidity. It considered in detail diverse cardiovascular disorders. This brings new insight into which parts of the population are vulnerable and which physiological mechanisms may be responsible for heat- and cold-related excess deaths.

The main findings of the study are as follow:

- Generally higher relative excess CVD mortality was identified on warm days than on cold days. Heat effects on mortality were significant also in the rural region. We did not find clear differences in heat and cold effects on CVD mortality between the two examined regions, except for higher heat-related mortality due to atherosclerosis in Prague and higher cold-related mortality due to myocardial infarction in southern Bohemia.
- While heat stress increases mortality especially due to chronic CVDs (atherosclerosis, chronic IHD), the effects of cold stress are most pronounced on acute CVDs (myocardial infarction). The different responses of individual CVDs to heat and cold stress represent an important finding that needs to be confirmed or adjusted for other populations, and it may be useful for issuing better-targeted heat- and cold-stress alerts.
- In contrast to mortality, insignificant excess hospital admissions for CVDs were observed on both warm and cold days. This may reflect the considerable number of people who die from acute CVDs before they can be admitted to the hospital, another primary cause for hospital admission (heat stroke, dehydration), or an increase in emergency visits in relation to less-severe incidents, which might account in part for the effect of temperature on morbidity.

The results on regional differences in population vulnerability between Prague and southern Bohemia indicate possible influence of both environmental (urban heat island effect and generally warmer climate of Prague, prolonged exposure to air pollution) and socioeconomic (such as different lifestyle and different population structure) factors. This should be taken into account when designing early warning systems as well as other measures toward preventing negative heat- and cold-stress effects on public health. The vulnerability needs to be further elaborated by examining spatial patterns of heat- and cold-related mortality in relation to environmental and socioeconomic patterns, a topic which has acquired increasing importance in recent years (Vescovi et al. 2005; Lougnan et al. 2008; Bayentin et al. 2010; Hattis et al. 2012).

Acknowledgements Thanks are due to B. Kříž and J. Kynčl, National Institute of Public Health, and P. Štěpánek, Czech Hydrometeorological Institute, for preparing epidemiological and meteorological datasets as well as for useful discussions concerning their interpretation. Comments of two anonymous reviewers helped improve the original manuscript in several important points. The study was supported by the Czech Science Foundation, project P209/11/1985.

Author Contributions Jan Kyselý defined the initial focus of this study. Aleš Urban together with Jan Kyselý carried out the final research design. Hana Hanzlíková was responsible for gathering and cleaning of the mortality and morbidity data as well as assistance with interpretation of physiological mechanisms causing different responses to heat and cold stress. Aleš Urban performed most analyses, prepared initial interpretation of results and drafted the first manuscript. All authors contributed to the final interpretation of results, and read and approved the final manuscript.

2.6 References

Abrignani MG, Corrao S, Biondo GB, et al. (2011) Effects of ambient temperature, humidity, and other meteorological variables on hospital admissions for angina pectoris. *Eur J Cardio Prevent Rehab* 0(00): 1–7. doi: 10.1177/1741826711402741

Arnfield AJ (2003) Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int J Climatol* 23: 1–26. doi: 10.1002/joc.859

Aylin P, Morris S, Wakefield J, et al. (2001) Temperature, housing, deprivation and their relationship to excess winter mortality in Great Britain, 1986-1996. *Int J Epidemiol* 30: 1100–1108.

Ballester J, Rodó X, Giorgi F (2009) Future changes in Central Europe heat waves expected to mostly follow summer mean warming. *Clim Dyn* 35: 1191–1205. doi: 10.1007/s00382-009-0641-5

Barriopedro D, Fischer EM, Luterbacher J et al.(2011) The hot summer of 2010: redrawing the temperature record map of Europe. *Science* 332: 220–4. doi: 10.1126/science.1201224

Basu R Samet JM (2002) Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. *Epidemiol Reviews* 24(2): 190–202. doi: 10.1093/epirev/mxf007

Bayentin L, El Adlouni S, Ouarda TBMJ, et al. (2010) Spatial variability of climate effects on ischemic heart disease hospitalization rates for the period 1989-2006 in Quebec, Canada. *Int J Health Geogr* 9: 5. http://www.ij-healthgeographics.com/content/9/1/5

Beranová R, Huth R (2005) Long-term changes in the heat island of Prague under different synoptic conditions. *Theor Appl Climatol* 82: 113–118. doi: 10.1007/s00704-004-0115-y

Bhaskaran K, Hajat S, Haines A, et al. (2010) Short term effects of temperature on risk of myocardial infarction in England and Wales: time series regression analysis of the Myocardial Ischaemia National Audit Project (MINAP) registry. *BMJ* 341: c3823. doi: 10.1136/bmj.c3823

Blatecká K (2006) *The Basic Characteristics of Czech rural areas*. Diploma thesis. Masaryk University Brno (in Czech, with summary in English). http://is.muni.cz/th/137827/esf m/Diplomova prace.pdf. Accessed 21 September 2012

Bobak M, Hertzman C, Skodova Z, et al. (1999) Socioeconomic status and cardiovascular risk factors in the Czech Republic. *Int J Epidemiol* 28: 46–52. doi: 10.1093/ije/28.1.46

Braga ALF, Zanobetti A, Schwartz J (2002) The effect of weather on respiratory and cardiovascular deaths in 12 U.S. cities. *Environ Health Perspect* 31:2173.

Brook RD, Franklin B, Cascio W, et al. (2004) Air pollution and cardiovascular disease: A statement for healthcare professionals from the expert panel on population and prevention science of the American Heart Association. *Circulation* 109: 2655–2671 doi: 10.1161/01.CIR.0000128587.30041.C8

Brown HK, Simpson AJ, Murchison JT (2009) The influence of meteorological variables on the development of deep venous thrombosis. *Thrombosis and Haemostasis* 102: 676–82. doi: 10.1160/TH09-04-0214

Carder M, McNamee R, Beverland I, et al. (2005) The lagged effect of cold temperature and wind chill on cardiorespiratory mortality in Scotland. *Occup Environ Med* 62: 702–710. doi: 10.1136/oem.2004.016394

Cheng X, Su H (2010) Effects of climatic temperature stress on cardiovascular diseases. *Eur J Intern Med* 21:164–167. doi: 10.1016/j.ejim.2010.03.001

Christidis N, Donaldson GC, Stott PA (2010) Causes for the recent changes in cold- and heat-related mortality in England and Wales. *Clim Change* 102: 539–553. doi: 10.1007/s10584-009-9774-0

Chuang K, Yan Y, Chiu S, et al. (2011) Long-term air pollution exposure and risk factors for cardiovascular diseases among the elderly in Taiwan. *Occup Environ Med* 68: 64–69. doi: 10.1136/oem.2009.052704

Conlon KC, Rajkovich NB, White-Newsome JL, et al. (2011) Preventing cold-related morbidity and mortality in a changing climate. *Maturitas* 69: 197–202. doi: 10.1016/j.maturitas.2011.04.004

Clark RA, Eckert KA, Stewart S, et al. (2007) Rural and urban differentials in primary care management of chronic heart failure: new data from the CASE study. *Med J Aus* 186: 441–5.

CZSO – Czech Statistical Office (2012). Statistical Yearbook 2011. http://www.czso.cz/csu/2011edicniplan.nsf/publ/0001-11-2010. Accessed 20 August 2012.

EEA – European Enviromental Agency (2010) Mapping the impacts of natural hazards and technological accidents in Europe: An overview of the last decade. Technical report No 13/2010. 144 pgs. http://www.eea.europa.eu/publications/mapping-the-impacts-of-natural. Accessed 21 September 2012

Ezekowitz MD (1992) Peripheral vascular disease. In: Zaret BL, Moser M, Hunt EK (eds). *The Yale University School of Medicine Heart Book.* New York: Heart Books. pp 205–214.

Dawson J, Weir C, Wright F, et al. (2008) Associations between meteorological variables and acute stroke hospital admissions in the west of Scotland. *Acta Neurol Scand* 117: 85–89. doi: 10.1111/j.1600-0404.2007.00916.x Journal

Feigin VL, Nikitin YP, Bots ML, et al. (2000) A population-based study of the associations of stroke occurrence with weather parameters in Siberia, Russia (1982-92). *Eur J Neurol* 7: 171–178.

Filleul L, Cassadou S, Médina S, et al. (2006) The relation between temperature, ozone, and mortality in nine French cities during the heat wave of 2003. *Environ Health Perspect* 114: 1344–1347. doi: 10.1186/1471-2458-6-261

Fischer EM, Oleson KW, Lawrence DM (2012) Contrasting urban and rural heat stress responses to climate change. *Geoph Res Lett* 39: L03705. doi: 10.1029/2011GL050576

Gabriel KMA, Endlicher WR (2011) Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. *Environ Pollut* 159: 2044–50. doi:10.1016/j.envpol.2011.01.016

Gosling SN, Lowe JA, McGregor GR, et al. (2009) Associations between elevated atmospheric temperature and human mortality: a critical review of literature. *Clim Change* 92(3–4): 299–341. doi: 10.1007/s10584-008-9441-x

Gravely-Witte S, Jurgens CY, Tamim H, et al. (2010) Length of delay in seeking medical care by patients with heart failure symptoms and the role of symptom-related factors: a narrative review. *Eur J Heart Fail* 12: 1122–1129. doi:10.1093/eurjhf/hfq122

Green RS, Basu R, Malig B, et al. (2010) The effect of temperature on hospital admissions in nine California counties. *Int J Public Health* 55: 113–121. doi: 10.1007/s00038-009-0076-0

Gómez-Acebo I, Dierssen-Sotos T, Llorca J (2010) Effect of cold temperatures on mortality in Cantabria (Northern Spain): a case-crossover study. *Public Health* 124: 398–403. doi:10.1016/j.puhe.2010.03.025

Hajat S, Kovats RS, Lachowycz K (2007) Heat-related and cold-related deaths in England and Wales: who is at risk? *Occup Environ Med* 64: 93–100. doi: 10.1136/oem.2006.029017

Hattis D, Ogneva-Himmelberger Y, Ratick S (2012) The spatial variability of heat-related mortality in Massachusetts. *Appl Geogr* 33: 45–52. doi: 10.1016/j.apgeog.2011.07.008

Henderson G (2005) Home air conditioning in Europe – how much energy would we use if we became more like American households? In: Attali S, Tillerson K (eds.). Energy Savings: What Works & Who Delivers? *ECEEE* 2005 Summer Study. pp 541–550.

Holmer B, Eliasson I (1999) Urban – rural vapour pressure differences and their role in the development of urban heat island. *Int J Climatol* 19: 989–1009.

Huynen MMTE, Martens P, Schram D, et al. (2001) The impact of heat waves and cold spells on mortality rates in the Dutch population. *Environ Health Perspect* 109: 463–470. doi: 10.2307/3454704

IHIS (2010) Activity of pathologic anatomy and forensic medicine in 2009. Prague: Institute of Health Information and Statistics of the Czech Republic. Fast information, Volume: 64/10.

IPCC (2007) Summary for Policymakers. In: *Climate Change 2007 The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M., Chen Z, Marquis M, Averyt KB, Tignor, M.and Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Junk J, Helbig A, Lüers J (2003) Urban climate and air quality in Trier Germany. *Int J Biometeorol* 47(4): 230–238. doi: 10.1007/s00484-003-0162-6

Kaufman JD (2012) Does air pollution accelerate progression of atherosclerosis? *J Am Coll Cardiol* 56: 1809–1811. doi: 10.1016/j.jacc.2010.05.054

Keatinge WR, Donaldson GC (2001) Mortality related to cold and air pollution in London after allowance for effects of associated weather patterns. *Medicine* 86: 209–216. doi: 10.1006/enrs.2001.4255

Knowlton K, Rotkin-Ellman M, King G, et al. (2009) The 2006 California heat wave: impacts on hospitalizations and emergency department visits. *Environ Health Perspect* 117: 61–67. doi: 10.1289/ehp.11594.

Kovats RS, Hajat S (2008) Heat stress and public health: a critical review. *Annu Rev Public Health* 29: 41–55. doi:10.1146/annurev.publhealth.29.020907.090843.

Kovats RS, Hajat S, Wilkinson P (2004) Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, UK. *Occup Environ Med* 61: 893–898. doi: 10.1136/oem.2003.012047

Kuttler W, Weber S, Schonnefeld J, et al. (2007) Urban/rural atmospheric water vapour pressure differences and urban moisture excess in Krefeld, Germany. *Int J Climatol* 27: 2005–2015. doi: 10.1002/joc.1558

Kyncl J, Prochazka B, Goddard NL, et al. (2005) A study of excess mortality during influenza epidemics in the Czech Republic, 1982–2000. *Eur J Epidemiol* 20: 365–371. doi:10.1007/s10654-005-1067-y

Kyobutungi C, Grau A, Stieglbauer G, et al. (2005) Absolute temperature, temperature changes and stroke risk: a case-crossover study. *Eur J Epidemiol* 20: 693–8. doi:10.1007/s10654-005-0703-x

Kyselý J (2004) Mortality and displaced mortality during heat waves in the Czech Republic. *Int J Biometeorol* 49: 91–97.

Kyselý J, Huth R (2004) Heat-related mortality in the Czech Republic examined through synoptic and "traditional" approaches. *Clim Res* 25: 265–274. doi: 10.3354/cr025265

Kyselý J, Kříž B (2008) Decreased impacts of the 2003 heat waves on mortality in the Czech Republic: an improved response? *Int J Biometeorol* 52: 733–745. doi: 10.1007/s00484-008-0166-3

Kyselý J, Pokorná L, Kynčl J, et al. (2009) Excess cardiovascular mortality associated with cold spells in the Czech Republic. *BMC Public Health* 9: 19. doi: 10.1186/1471-2458-9-19

Kyselý J, Plavcová E (2010) A critical remark on the applicability of E-OBS European gridded temperature dataset for validating control climate simulations. *J Geoph Res* 115: D23118. doi: 10.1029/2010JD014123

Kyselý J, Plavcová E (2012) Declining impacts of hot spells on mortality in the Czech Republic, 1986–2009: adaptation to climate change? *Clim Change* 113: 437–453. doi: 10.1007/s10584-011-0358-4

Kyselý J, Plavcová E, Davídkovová H, et al. (2011) Comparison of hot and cold spell effects on cardiovascular mortality in individual population groups in the Czech Republic. *Clim Res* 49: 113–129. doi: 10.3354/cr01014

Laschewski G, Jendritzky G (2002) Effects of the thermal environment on human health: an investigation of 30 years of daily mortality data from SW Germany. *Clim Res* 21: 91–103. doi: 10.3354/cr021091

Linares C, Díaz J (2008) Impact of high temperatures on hospital admissions: comparative analysis with previous studies about mortality (Madrid). *Eur J Public Health* 18: 317–22. doi: 10.1093/eurpub/ckm108

Loughnan ME, Nicholls N, Tapper NJ (2008) Demographic, seasonal, and spatial differences in acute myocardial infarction admissions to hospital in Melbourne Australia. *Int J Health Geogr* 7: 42. doi: 10.1186/1476-072X-7-42

Ma W, Xu X, Peng L, et al. (2011) Impact of extreme temperature on hospital admission in Shanghai, China. *Sci Total Environ* 409: 3634–3637. doi:10.1016/j.scitotenv.2011.06.042

Maitre A, Bonneterre V, Huillard L, et al. (2006) Impact of urban atmospheric pollution on coronary disease. *Eur Heart J* 27: 2275–2284. doi: 10.1093/eurheartj/ehl162.

Mastrangelo G, Fedeli U, Visentin C, et al. (2007) Pattern and determinants of hospitalization during heat waves: an ecologic study. *BMC Public Health* 7: 200. doi: 10.1186/1471-2458-7-200.

McMichael AJ, Woodruff RE, Hales S (2006) Climate change and human health: present and future risks. *Lancet* 367: 859–869. doi: 10.1016/S0140-6736(06)68079-3

Medina-Ramón M, Schwartz J (2007) Temperature, temperature extremes, and mortality: a study of acclimatization and effect modification in 50 United States cities. *Occup Environ Med* 64: 827–833. doi: 10.1136/oem.2007.033175

Mercer JB (2002) Cold – an underrated risk factor for health. *Environ Res Environ Res* 92: 8–13. doi: 10.1016/S0013-9351(02)00009-9

Michelozzi P, Accetta G, De Sario M, et al. (2009) High temperature and hospitalizations for cardiovascular and respiratory causes in 12 European cities. *Am J Respir Crit Care Med* 179: 383–389. doi: 10.1164/rccm.200802-217OC

Mikeszova M (2010) *Bezdomovství v Praze a ve větších městech Středočeského kraje* (Homelessness in Prague and in the larger cities of the Central Bohemian Region). http://www.socioweb.cz/index.php?disp=temata&shw=346&lst=106. Accessed 23 August 2012

Mills G (2004) The urban canopy layer heat island. IAUC Teaching Resources. pp 1–5. http://www.urban-climate.org/UHI_Canopy.pdf. Accessed 23 August 2012.

Mills G (2007) Cities as agents of global change. *Int J Climatol* 27: 1849–1857. doi: 10.1002/joc.1604

Morabito M, Modesti PA, Cecchi L, et al. (2005) Relationships between weather and myocardial infarction: a biometeorological approach. *Int J Cardiol* 105: 288–293. doi:10.1016/j.ijcard.2004.12.047

Morabito M, Crisci A, Grifoni D, et al. (2006) Winter air-mass-based synoptic climatological approach and hospital admissions for myocardial infarction in Florence, Italy. *Environ Res Environ Res* 102: 52–60. doi:10.1016/j.envres.2005.12.007

O'Neill MS, Carter R, Kish JK, et al. (2009) Preventing heat-related morbidity and mortality: new approaches in a changing climate. *Maturitas* 64: 98–103. doi:10.1016/j.maturitas.2009.08.005

Rudge J, Gilchrist R (2005) Excess winter morbidity among older people at risk of cold homes: a population-based study in a London borough. *J Public Health* 27: 353–358. doi: 10.1093/pubmed/fdi051

Schoenberg BS (1983) Calculating confidence intervals for rates and ratios. *Neuroepidemiology* 2: 257–265

Schwartz J, Samet JM, Patz JA (2004) Hospital admissions for heart disease the effects of temperature and humidity. *Epidemiology* 15: 755–761. doi: 10.1097/01.ede.0000134875.15919.0f

Semenza JC, Mccullough JE, Flanders WD, et al. (1999) Excess hospital admissions during the July 1995 heat wave in Chicago. *Am J Prevent Med* 16: 269–277.

Sheridan SC, Dolney TJ (2003) Heat, mortality, and level of urbanization: measuring vulnerability across Ohio, USA. *Clim Res* 24: 255–265

Sheridan SC, Kalkstein AJ, Kalkstein LS (2008) Trends in heat-related mortality in the United States, 1975–2004. Nat Hazards 50: 145–160. doi:10.1007/s11069-008-9327-2

Smoyer KE, Kalkstein LS, Greene JS, et al. (2000) The impacts of weather and pollution on human mortality in Birmingham, Alabama and Philadelphia, Pennsylvania. *Int J Climatol* 20: 881–897

Smoyer KE, Rainham DG, Hewko JN (2000) Heat-stress-related mortality in five cities in Southern Ontario: 1980–1996. *Int J Biometeorol* 44:190–197

Spiezia V (2003) Measuring regional economies. Statistics Brief OECD, No. 6, October 2003. http://www.oecd.org/dataoecd/2/15/15918996.pdf. Accessed 21 September 2012

Tan J, Zheng Y, Tang X, et al. (2010) The urban heat island and its impact on heat waves and human health in Shanghai. *Int J Biometeorol* 54: 75–84 doi: 10.1007/s00484-009-0256-x

Tanis B (2003) Oral contraceptives and the risk of myocardial infarction. Eur Heart J 24:377–380. doi: 10.1016/S0195-668X(02)00752-2

The Eurowinter Group (1997) Cold exposure and winter mortality from ischæmic heart disease, cerebrovascular disease, respiratory disease, and all causes in warm and cold regions of Europe. *Lancet* 349: 1341–1346

Trusilova K, Jung M, Churkina G, et al. (2008) Urbanization impacts on the climate in Europe: numerical experiments by the PSU–NCAR Mesoscale Model (MM5). *J Appl Meteorol Climatol* 47: 1442–1455. doi: 10.1175/2007JAMC1624.1

Vaneckova P, Neville G, Tippett V, et al. (2011) Do biometeorological indices improve modeling outcomes of heat-related mortality? *J Appl Meteorol Climatol* 50: 1165–1176. doi: 10.1175/2011JAMC2632.1

Vescovi L, Rebetez M, Rong F (2005) Assessing public health risk due to extremely high temperature events: climate and social parameters. *Clim Res* 30: 71–78. doi: 10.3354/cr030071

Vobecká J (2009) The commuting approach to delimiting urban, suburban, and rural populations in the Czech Republic. *Demografie* 51: 14–22. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1663043. (in Czech, with summary in English). Accessed 17 August 2012.

Wang XU, Barnett AG, Hu W, et al. (2009) Temperature variation and emergency hospital admissions for stroke in Brisbane, Australia, 1996–2005. *Int J Biometeorol* 53: 535–541.

White RH (2003) The epidemiology of venous thromboembolism. *Circulation* 107: I4–8. doi: 10.1161/01.CIR.0000078468.11849.66

Whitman S, Good G, Donoghue ER, et al. (1997) Mortality in Chicago attributed to the July 1995 heat wave. *Amer J Pub Health* 87: 1515–1518.

Ye X, Wolff R, Yu W, et al. (2012) Ambient temperature and morbidity: a review of epidemiological evidence. *Environ Health Perspect* 120: 19–28. doi: 10.1289/ehp.1003198

3 Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic

Aleš Urban [1,2], Jan Kyselý [1]

[1] *Institute of Atmospheric Physics AS CR, Boční II 1401, 141 31 Prague 4, Czech Republic*

[2] *Faculty of Science, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic*

Abstract: We compare the recently developed Universal Thermal Climate Index (UTCI) with other thermal indices in analysing heat- and cold-related effects on cardiovascular (CVD) mortality in two different (urban and rural) regions in the Czech Republic during the 16-year period of 1994–2009. Excess mortality is represented by the number of deaths above expected daily values, the latter being adjusted for long-term changes, annual and weekly cycles, and epidemics of influenza/acute respiratory infections. Air temperature, UTCI, Apparent Temperature (AT) and Physiologically Equivalent Temperature (PET) are applied to identify days with heat and cold stress. We found similar heat effects on CVD mortality for air temperature and the examined thermal indices. Responses of CVD mortality to cold effects as characterised by different indices were much more varied. Particularly important is the finding that air temperature provides a weak cold effect in comparison with the thermal indices in both regions, so its application – still widespread in epidemiological studies – may underestimate the magnitude of cold-related mortality. These findings are important when possible climate change effects on heat- and cold-related mortality are estimated. AT and PET appear to be more universal predictors of heat- and cold- related mortality than UTCI when both urban and rural environments are of concern. UTCI tends to select windy rather than freezing days in winter, though these show little effect on mortality in the urban population. By contrast, significant cold-related mortality in the rural region if UTCI is used shows potential for UTCI to become a useful tool in cold exposure assessments.

Keywords: UTCI; human thermal comfort; mortality; cardiovascular diseases; heat stress; cold stress

3.1 Introduction

An adverse effect of heat and cold stress on mortality due to cardiovascular diseases has been reported in many studies (Cheng and Su 2010). Most of these employed air temperature or another simple measure of equivalent temperature (empirical indices) including effects of air temperature, humidity and/or wind speed (apparent temperature, heat index etc.; Basu 2009). Human thermal comfort is an outcome of energy balance between the human body surface and the environment, and it is influenced by human physiology, psychology and behaviour (McGregor 2011; Jendritzky et al. 2012). Not all of these factors are well characterized by empirical indices, which, therefore, are unable to serve all human-biometeorological applications (e.g. public weather service, public health system, urban and regional planning, climate impact in the health sector) across all climatic zones, regions and seasons (Jendritzky et al. 2012).

Human thermal comfort models, on the other hand, consider in addition to atmospheric parameters (air temperature, water vapour pressure, wind speed and mean radiant temperature (Kántor and Unger 2011) complex metabolic processes including physical activity level and clothing insulation (Jendritzky et al. 2012). Human thermal comfort indices such as Physiologically Equivalent Temperature (PET; Mayer and Höppe 1987; Höppe 1999; Matzarakis et al. 1999) based on the Munich Energy–Balance Model for Individuals (MEMI) and the Klima–Michel model with Perceived Temperature (PT) as the equivalent temperature (Jendritzky 2000; Staiger et al. 2012) have been commonly used in human-biometeorological assessments during the last decade (Laschewski et al. 2002; Matzarakis et al. 2010a; Burkart et al. 2011a; Gabriel and Endlicher 2011; Kim et al. 2011; Nastos and Matzarakis 2011). One of the most advanced models based on the latest progress in all associated disciplines (thermal physiology, occupational medicine, physics, meteorology, as well as biometeorological and environmental sciences) is the Fiala multi-node model of human thermoregulation (Fiala et al. 2012) with a derived equivalent temperature Universal Thermal Climate Index (UTCI). It has been developed in order to create a standard measure for outdoor thermal conditions suitable in all major fields of human biometeorology (Jendritzky et al. 2012; www.utci.org). The Fiala thermophysiological model is coupled with a clothing model which defines in detail the effect of clothing insulation for each of the body segments over a wide range of climatic conditions (Havenith et al. 2012). UTCI, in comparison with other indices, is more sensitive to even slight changes in temperature, solar radiation, humidity and wind speed and describes better various climatic conditions, which might be an opportunity for more appropriate human-biometeorological assessments (Błażejczyk et al. 2012).

Błażejczyk et al. (2012) compared UTCI with other indices using meteorological data. Only a few studies, however, have evaluated how UTCI performs compared to other indices in assessing epidemiological outcomes (Burkart et al. 2011a; Nastos and Matzarakis 2011), and their results have been unconvincing. Indeed, no significant predictive advantage for any thermal index (including UTCI) over the use of air temperature has been observed. Both aforementioned studies were carried out in a warm climate (Bangladesh and Greece), and there have been no studies comparing the applicability of various human thermal comfort indices for studying heat- and cold-related mortality in populations living under temperate climatic conditions (such as central Europe).

Recent epidemiological data available in the Czech Republic allow for more detailed study of heat and cold stress impacts on individual cardiovascular (CVD) diagnoses (groups of diagnoses) and enable the study of regional differences within the country. This paper resumes our earlier research (Urban et al. 2014) and investigates differences in heat- and cold-related cardiovascular mortality evaluated in terms of different thermal indices in an urban and a rural region in the Czech Republic. In the context of a complex thermal environment, we compared UTCI with other thermal indices and with air temperature for their abilities to identify days with adverse thermal conditions for persons with cardiovascular diseases. A special focus was given to differences in the performance of various indices under cold stress conditions due to the effect of wind.

3.2 Data and Methods

Daily data on mortality due to CVDs (codes I00–I99 according to the International Statistical Classification of Diseases, 10th Revision [ICD–10]), covering the period 1994–2009, were provided by the Czech Statistical Office (CZSO) and the Institute of Health Information and Statistics (IHIS). The data were sorted according to the primary cause of death (Table 3.1) and region of residence. Two regions with different characteristics – the city of Prague (1.25 million inhabitants) and the southern Bohemian region (1.15 million inhabitants) – were defined as urban and rural regions in accordance with the OECD's international definition (Spiezia 2003; Blatecká 2006). OECD's terminology (Spiezia 2003) defines a rural region as one in which at least 37.5% of inhabitants live in municipalities with population density less than 150 inhabitants per 1 km^2. In accordance with this definition, the two regional administrative units in the Czech Republic with the largest proportions of rural population are the South Bohemia Region (Jihočeský kraj, 46.8%) and the adjoining Highlands Region (Kraj Vysočina, 51.9%) (Blatecká 2006). Together, these constitute a contiguous geographic region (southern Bohemia; Figure 3.1) with population size and structure similar to Prague, but only 36% of inhabitants live in municipalities with population above 10,000 (CZSO 2012). More details about the population under study are given in (Urban et al. 2014).

An indirect standardization procedure, analogous to that in (Whitman et al. 1997; Smoyer et al. 2000), was used to adjust mortality data for long-term changes, as well as seasonal and weekly variations. The expected number of deaths for every day of the examined period $M_0(y,d)$ for year y (y = 1994, ... 2009) and day d (d = 1, ... 365) was determined according to the formula

$$M_0(y,d) = M_0(d).W(y,d).Y(y)$$

In the equation, $M_0(d)$ denotes the mean daily mortality on day d in a year (computed from the mean annual cycle over 1994–2009). In view of known relationships between influenza/acute respiratory infections (ARI) and CVD mortality (Kynčl et al. 2005; Kyselý et al. 2009), 169 winter days during 6 epidemics were omitted from the analysis (before calculating the mean annual cycle) in order not to confound results (see also Urban et al. 2014). $W(y,d)$ is a correction factor for the observed weekly cycle of mortality, calculated separately for individual days of the week and defined as the ratio of the mean mortality on a given day to the overall mean mortality, and $Y(y)$ is a correction factor for the observed year-to-year changes in mortality, defined as the ratio of the number of deaths in year y to the mean annual number of deaths during the analyzed period. The correction factors for the weekly cycle $W(y,d)$ and the year-to-year changes $Y(y)$ were calculated over the April–November period when epidemics of influenza/ARI did not occur. When calculating $W(y,d)$, all public holidays were excluded, too. An output of the standardization procedure is an expected number of deaths for every day of the examined period (baseline mortality), and deviations of observed and expected mortality determine excess mortality. Relative deviations (in %) from the baseline mortality are presented in results.

Table 3.1 Examined diagnoses according to the International Statistical Classification of Diseases (ICD–10) coding and abbreviations used.

ICD–10 code	Abbreviation	Diagnosis
I00–I99	CVD	cardiovascular disease
I20–I25	IHD	ischemic heart disease
I60–I69	CD	cerebrovascular disease
I21–I22	MI	myocardial infarction (acute and subsequent)
I25	CIHD	chronic ischemic heart disease
I70	ASVD	atherosclerosis – atherosclerotic vascular disease

Because of the need for more input variables, different meteorological datasets were used in comparison to those from our previous study (Gabriel and Endlicher 2011). Data on air temperature (*T*, in °C), wind speed at 10 m above surface (v_{10}, m·s^{-1}), relative humidity (*RH*, %) and cloudiness (*C*, octas) from the Prague–Ruzyně (airport) station and three southern Bohemian stations (České Budějovice, Kostelní Myslová, Přibyslav), were obtained from the Czech Hydrometeorological Institute (CHMI; Figure 3.1). All stations measured 3 times daily in standard climatic terms (7:00, 14:00 and 21:00 local time) and covered the same period of 1994–2009.

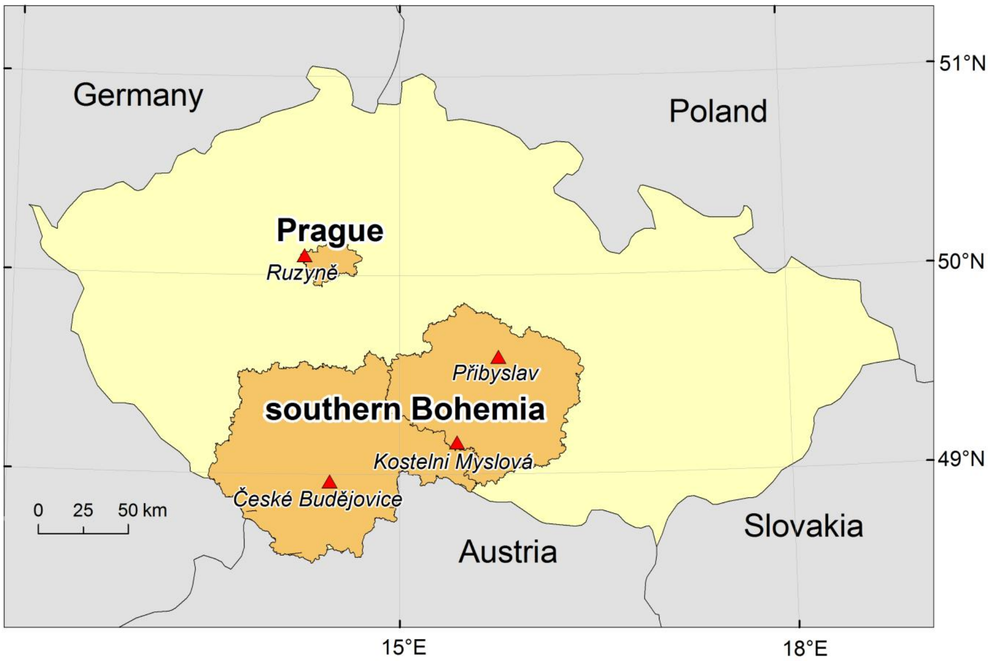

Figure 3.1 Study areas. *Red triangles* show meteorological stations used.

The heat budget-based indices – PET and UTCI – were calculated from air temperature, relative humidity, wind speed, and mean radiant temperature (Tmrt) that was modelled as a function of air temperature and cloudiness, in the RayMan Pro model (Version 2.1)

(Matzarakis et al. 2007; Matzarakis et al. 2010b). For the calculation of PET, it is necessary to consider meteorological input parameters important for the human energy balance at a height relevant for human-biometeorological assessment (Mayer and Höppe 1987; Höppe 1999). Therefore, the wind speed was recalculated to the height of 1.1 m above surface, using Hellmann exponential law (Bañuelos-Ruedas and Camacho 2011):

$$\frac{v}{v_{10}} = \left(\frac{H}{H_{10}}\right)^{\alpha}$$

where v is the wind speed at height H = 1.1 m, v_{10} is the wind speed at height H_{10} = 10 m, and α is the friction coefficient (Hellman exponent). We used α=0.40 for the urban area (Prague) and α = 0.30 for the rural area according to Table 3.1 in (Bañuelos-Ruedas and Camacho 2011). PET is then defined as an equivalent temperature in a typical indoor setting (without wind and solar radiation) at which the energy balance of the sitting reference person (with the same core and skin temperature) is equal to that under the actual outdoor conditions to be assessed (Höppe 1999). We note that the reference height at which wind speed is considered when calculating PET is important for the PET values but has little influence on the selection of warm/cold days (above/below the 90%/10% quantile) in our study, as the samples of warm and cold days were very similar if PET was calculated from wind speed at 10-m height.

UTCI is an equivalent temperature defined for a walking person (4 km/h) with adaptive clothing (Havenith et al. 2012) in referent outdoor conditions with 50% relative humidity, still air, and Tmrt equalling air temperature (Jendritzky et al. 2012). Wind speed at 10-m height is used for the UTCI calculation (by definition) (Bröde et al. 2012). Apparent Temperature (AT) is the temperature at the reference humidity level requiring the same thermal resistance of a walking adult as that experienced under the current ambient temperature, humidity, wind and solar radiation (Steadman 1984). The Steadman's "non-radiation" formula (Steadman 1984; Steadman 1994) was used for the AT calculation: AT = $T + 0.33 \cdot vp - 0.7 \cdot v_{10} - 4.0$. Since it includes in addition to vapour pressure (vp) also the "wind chill" effect of wind speed (v_{10}), AT is applicable in a wide range of temperatures. Vapour pressure values were calculated from air temperature and humidity in the RayMan Pro model. All indices were computed separately for every station at each observation time (7:00, 14:00 and 21:00 local time) and then averaged to obtain mean daily values.

Days with mean (equivalent) temperature (T, AT, PET, and UTCI) above/below the 90%/10% quantile of the empirical distribution in summer (June–August)/winter (December–February) seasons over 1994–2009 were defined as *warm*/*cold* days. Use of the percentile method (unlike determining an exact temperature threshold) allows for examining approximately the same sample sizes in different regions and at both temperature extremes. This method has commonly been used for regional comparison of heat and cold impact on human health (Hajat et al. 2007; Medina-Ramón and Schwartz 2007; Gómez-Acebo et al. 2010; Gabriel and Endlicher et al. 2011). Because some winter days were omitted due to influenza/ARI epidemics, and also because winter seasons (usually 90 days) are shorter than summer seasons (92 days), the examined samples of cold days are slightly smaller than those of warm days.

Summed and averaged deviations from the expected values of mortality over all warm/cold days (D_0) and one day thereafter (D_{+1}, to capture basic lagged effects) were calculated. In the case of consecutive warm/cold days, only D_0 values were included into the calculation so that no day is counted twice. The deviations' significance was evaluated using 95% confidence intervals (CI), calculated using the limit factors for a Poisson-distributed variable according to (Schoenberg 1983). When the number of cases was larger than 100, the normal approximation was used.

3.3 Results

On warm days in both regions, excess mortality tends to be highest when AT is used to determine those days (Figure 3.2). This holds true for all examined groups of diagnoses except for atherosclerosis (ASVD) (Table 3.2). We found similar urban–rural differences for all indices, with slightly higher mortality deviations in the urban region. This pattern holds true also for most examined groups of diagnoses.

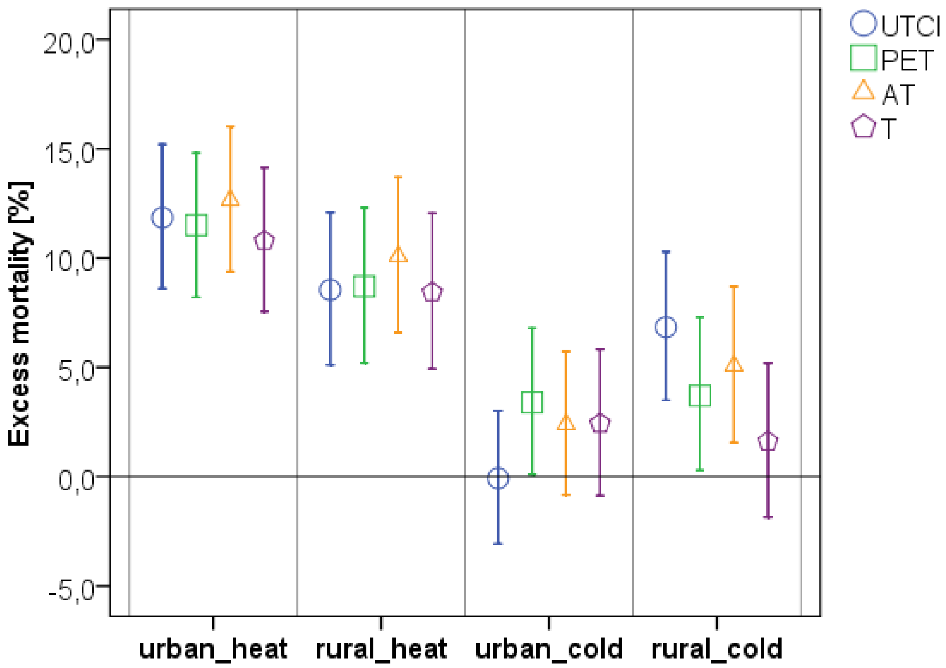

Figure 3.2 Mean relative excess CVD mortality (% above the expected value) for warm and cold days as determined by individual indices in the urban versus rural region. *Error bars* represent the 95% CI (specific values are given in Tables 3.2 and 3.3).

Table 3.2 Relative excess cardiovascular mortality with 95% CI (in parentheses) on warm days, defined as days with average (equivalent) temperature above the 90% quantile of the empirical distribution (≥ °C), in Prague and southern Bohemia over 1994–2009. Values significantly different from zero are highlighted in bold.

		Urban region (Prague)		
Thermal index/ Diagnosis	**UTCI (≥ 22.0 °C)**	**PET (≥ 19.2 °C)**	**AT (≥ 22.0 °C)**	**T (≥ 22.5 °C)**
CVD	**11.8 (8.6; 15.2)**	**11.5 (8.2; 14.8)**	**12.6 (9.4; 16.0)**	**10.8 (7.5; 14.1)**
IHD	**7.8 (2.9; 13.0)**	**8.0 (3.0; 13.2)**	**8.7 (3.7; 13.9)**	**7.0 (2.1; 12.2)**
CD	**11.6 (5.4; 18.2)**	**9.5 (3.3; 16.1)**	**13.0 (6.7; 19.7)**	**10.0 (3.8; 16.6)**
MI	−0.8 (−8.8; 7.9)	1.5 (−6.6; 10.4)	−0.2 (−8.2; 8.5)	−1.6 (−9.6; 7.1)
CIHD	**12.0 (5.8; 18.6)**	**10.9 (4.7; 17.5)**	**13.0 (6.8; 19.7)**	**10.9 (4.7; 17.4)**
ASVD	**17.6 (10.0; 25.7)**	**18.5 (10.9; 26.6)**	**18.5 (10.9; 26.5)**	**19.4 (11.6; 27.7)**

		Rural region (southern Bohemia)		
Thermal index/ Diagnosis	**UTCI (≥ 21.9 °C)**	**PET (≥ 18.0 °C)**	**AT (≥ 21.7 °C)**	**T (≥ 22.0 °C)**
CVD	**8.5 (5.1; 12.1)**	**8.7 (5.2; 12.3)**	**10.1 (6.6; 13.7)**	**8.4 (4.9; 12.0)**
IHD	**6.9 (2.0; 12.0)**	**7.3 (2.3; 12.5)**	**7.9 (2.9; 13.2)**	**7.2 (2.2; 12.5)**
CD	**11.4 (5.0; 18.3)**	**10.3 (3.8; 17.2)**	**13.5 (6.9; 20.6)**	**7.9 (1.3; 14.8)**
MI	1.6 (−5.6; 9.4)	1.2 (−6.1; 9.1)	2.0 (−5.4; 9.9)	3.6 (−3.9; 11.8)
CIHD	**11.4 (4.8; 18.4)**	**11.9 (5.2; 19.0)**	**12.4 (5.6; 19.5)**	**10.2 (3.5; 17.4)**
ASVD	**9.8 (0.4; 20.2)**	**10.9 (1.4; 21.3)**	**11.2 (1.5; 21.8)**	**14.9 (5.0; 25.6)**

All indices fit well with one another in summer (Table 3.3, Figure 3.3). PET and AT fit equally well with UTCI (the coefficient of determination [r^2] is around 0.93, and there are about 83% warm days in common for these pairs of indices in both regions), although the AT calculation does not include the effect of Tmrt. The relationship between air temperature and UTCI is weaker (about 75% warm days in common). The average Tmrt values were very similar for all indices on warm days, however, and the other input meteorological variables (T, v_{10}, RH, C) also showed few differences in the two regions (Table 3.4).

Table 3.3 Coefficients of determination (r^2) for linear relationships between mean daily UTCI, PET, AT, and T in the urban versus rural region in summer (JJA) and winter (DJF) seasons. [%] denotes percentages of warm (cold) days in common in summer (winter) during 1994–2009.

	Urban JJA		Urban DJF		Rural JJA		Rural DJF	
	r^2	[%]	r^2	[%]	r^2	[%]	r^2	[%]
T~UTCI	0.83	73	0.23	31	0.86	77	0.52	45
PET~UTCI	0.91	82	0.41	39	0.92	82	0.68	59
AT~UTCI	0.93	83	0.56	45	0.94	84	0.75	62
T~AT	0.94	79	0.88	86	0.95	84	0.94	81
AT~PET	0.98	82	0.95	91	0.98	87	0.98	91
T~PET	0.96	84	0.95	88	0.95	87	0.96	80

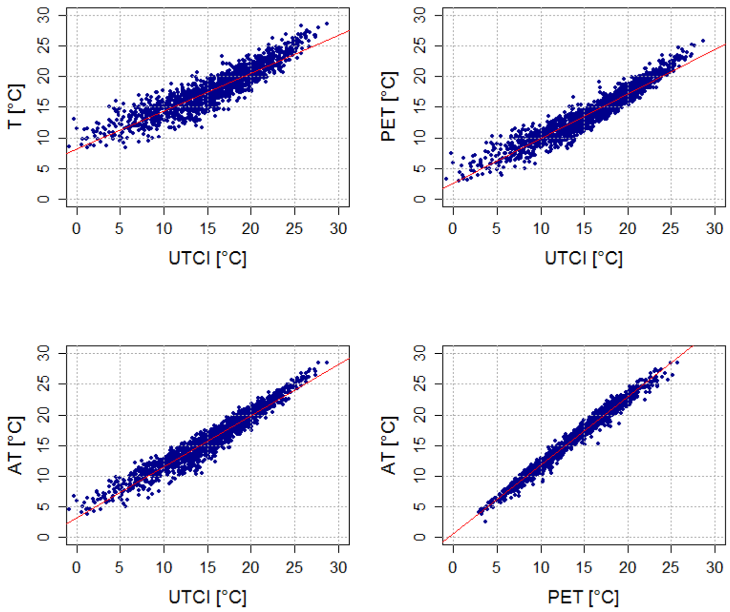

Figure 3.3 Linear regression between mean daily UTCI, PET, AT, and T in the urban (Prague) region in summer over 1994–2009. Coefficients of determination are shown in Table 3.3.

Table 3.4 Average values of (equivalent) temperature indices and input meteorological variables on warm days identified by individual indices in urban versus rural region.

Urban region	UTCI (°C)	PET (°C)	AT (°C)	*T* (°C)	Tmrt (°C)	v_{10} (m·s⁻¹)	*RH* (%)	*C* (octas)
UTCI	23.9	20.8	23.7	23.8	29.7	2.3	59	3.7
PET	23.7	21.0	23.7	24.0	29.8	2.6	58	3.9
AT	23.8	20.8	23.8	24.0	29.6	2.5	60	3.5
T	23.4	20.8	23.5	24.2	29.8	2.9	56	3.3

Rural region	UTCI (°C)	PET (°C)	AT (°C)	*T* (°C)	Tmrt (°C)	v_{10} (m·s⁻¹)	*RH* (%)	*C* (octas)
UTCI	23.4	19.3	23.2	23.2	28.8	2.2	62	2.6
PET	23.2	19.4	23.2	23.3	28.7	2.4	61	2.6
AT	23.3	19.4	23.3	23.3	28.6	2.4	63	2.5
T	23.1	19.3	23.2	23.5	28.9	2.6	60	2.4

On cold days, by contrast, we found no general pattern of higher excess mortality for any index (Figure 3.2) and the results depend on region and diagnosis (Table 3.5). The urban–rural differences in cold-related mortality for individual indices are much less consistent compared to heat-related mortality. While mean excess mortality is comparable (predominantly insignificant differences) for PET, AT and *T* in Prague, it is higher and mostly significant for UTCI and AT in southern Bohemia. In particular, UTCI indicates substantial difference between no cold effect (−0.1%, 95% confidence interval (CI) −3.1 to 3.0%) on CVD mortality in Prague but significant 6.8% (3.5% to 10.3%) excess mortality in southern Bohemia, a pattern that is not found for any other index.

UTCI correlates weakly with the other indices and air temperature in winter (Table 3.3, Figure 3.4), while PET and AT are much more strongly linked to air temperature. Moreover, little consensus in the selection of cold days between UTCI and the other indices was found in the two regions. In Prague, only 31% of cold days were common for air temperature and UTCI, and the r^2 for all winter daily values of T and UTCI was just 0.23.

Examining specific diagnoses and groups of diagnoses, the general pattern of heat-related mortality was associated primarily with chronic CVDs (atherosclerosis [ASVD], chronic ischemic heart disease [CIHD]) while the highest cold-related mortality from acute myocardial infarction (MI) observed in both regions and for all indices was in agreement with our previous study based on air temperature only (Urban et al. 2014). However, while the heat-related mortality deviations show a similar pattern of differences between individual diagnoses (with the largest deviations for ASVD and the lowest for ischemic heart disease [IHD] and MI) for all indices (Table 3.2), the differences in excess mortality for individual groups of diagnoses on cold days are much less consistent (Table 3.5). UTCI and AT indicate significant (p = 0.05) excess mortality in the rural region also for both main subgroups of CVDs (IHD and cerebrovascular disease [CD]). This is in contrast with the results for air temperature, in relation to which excess cold-related mortality is very small in both regions and all diagnoses, except for MI.

Table 3.5 Relative excess cardiovascular mortality with 95% CI (in parentheses) on cold days, defined as days with average (equivalent) temperature above the 90% quantile of the empirical distribution (≤ °C), in Prague and southern Bohemia over 1994–2009. Values significantly different from zero are highlighted in bold.

Urban region (Prague)				
Thermal index/ Diagnosis	**UTCI (≤ −21.5 °C)**	**PET (≤ −12.9 °C)**	**AT (≤ −12.1 °C)**	***T* (≤ −6.5 °C)**
CVD	−0.1 (−3.1; 3.0)	**3.4 (0.1; 6.8)**	2.4 (−0.8; 5.7)	2.4 (−0.9; 5.8)
IHD	−0.6 (−5.4; 4.3)	3.9 (−1.4; 9.4)	3.8 (−1.3; 9.3)	2.1 (−3.1; 7.6)
CD	0.9 (−5.0; 7.2)	4.6 (−2.0; 11.5)	4.1 (−2.3; 11.0)	4.6 (−2.0; 11.6)
MI	4.5 (−3.6; 13.3)	**10.6 (1.3; 20.7)**	**10.5 (1.4; 20.4)**	7.1 (−2.1; 17.1)
CIHD	−3.1 (−8.9; 3.0)	0.6 (−5.7; 7.3)	0.5 (−5.8; 7.1)	−0.3 (−6.7; 6.5)
ASVD	1.7 (−4.7; 8.5)	3.6 (−3.4; 11.1)	1.4 (−5.2; 8.5)	2.8 (−4.0; 10.1)

Rural region (southern Bohemia)				
Thermal index/ Diagnosis	**UTCI (≤ −19.9 °C)**	**PET (≤ −13.5 °C)**	**AT (≤ −12.4 °C)**	***T* (≤ −7.3 °C)**
CVD	**6.8 (3.5; 10.3)**	**3.7 (0.3; 7.3)**	**5.1 (1.6; 8.7)**	1.6 (−1.9; 5.2)
IHD	**8.3 (3.4; 13.5)**	3.3 (−1.8; 8.5)	**5.7 (0.6; 11.1)**	2.0 (−3.1; 7.4)
CD	**10.7 (4.4; 17.3)**	**7.0 (0.5; 14.0)**	**8.0 (1.4; 15.1)**	2.7 (−3.8; 9.5)
MI	**15.2 (7.4; 23.6)**	**12.6 (4.4; 21.4)**	**17.2 (8.8; 26.2)**	**10.6 (2.4; 19.5)**
CIHD	2.9 (−3.4; 9.6)	−3.5 (−9.8; 3.2)	−2.7 (−9.1; 4.2)	−4.3 (−10.7; 2.6)
ASVD	−1.5 (−10.3; 8.2)	−1.4 (−10.7; 8.8)	−1.7 (−11.1; 8.7)	1.5 (−7.9; 11.9)

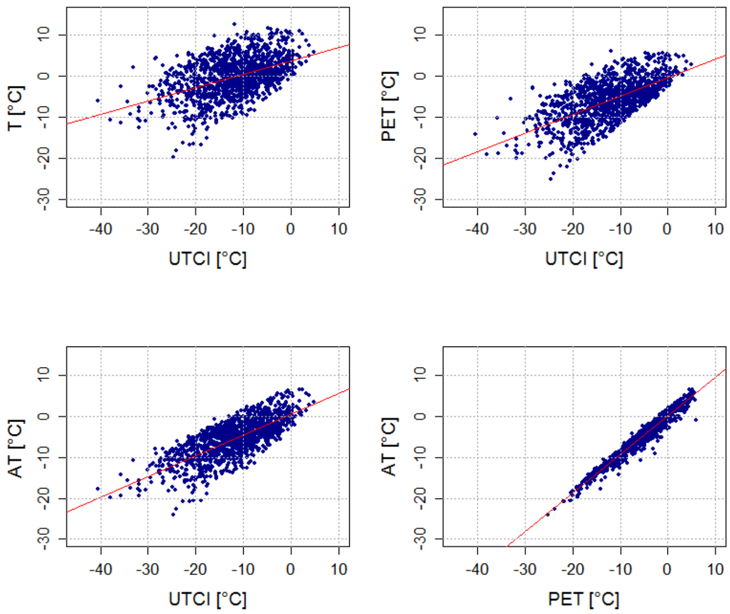

Figure 3.4 Linear regression between mean daily UTCI, PET, AT, and *T* in the urban (Prague) region in winter over 1994–2009. Coefficients of determination are shown in Table 3.3.

3.4 Discussion

In this study, we tested the extent to which UTCI, other thermal indices (PET, AT), and air temperature are able to identify days with adverse thermal conditions for persons with cardiovascular diseases (CVD). While similar heat effects for air temperature and thermal indices on cardiovascular (CVD) mortality were found in both urban and rural region of the Czech Republic, we observed no general pattern of higher excess mortality for any index on cold days and the urban–rural differences in cold-related mortality were much less consistent compared to heat-related mortality. In particular, UTCI indicates substantial difference between no cold effect on CVD mortality in Prague but significant excess mortality in southern Bohemia.

The different cold effects of air temperature and thermal indices are related to the different samples of cold days for individual indices (Table 3.6). The enhanced cooling effect of wind involved in the UTCI calculation (Błażejczyk et al. 2012) is probably the main reason for this dissimilarity. While the average wind speed at Prague-Ruzyně airport on cold days is approximately twice as high for UTCI (7.2 m·s^{-1}) in comparison to the other indices (2.6–3.4 m·s^{-1}), average air temperature is higher as well (−4.4 °C versus −9.3 to −9.6 °C; Table 3.6). Also the other meteorological variables, in particular Tmrt, show substantially different average values on cold days as defined by UTCI in comparison to those defined by the other indices. A similar pattern exists in the rural area.

Table 3.6 Average values of (equivalent) temperature indices and input meteorological variables on cold days identified by individual indices in urban versus rural region.

Urban region	UTCI (°C)	PET (°C)	AT (°C)	*T* (°C)	Tmrt (°C)	v_{10} (m·s^{-1})	*RH* (%)	*C* (octas)
UTCI	−25.5	−11.5	−12.2	−4.4	−9.0	7.2	81	5.7
PET	−20.9	−15.7	−14.7	−9.3	−16.3	3.2	83	4.0
AT	−21.4	−15.6	−14.8	−9.3	−16.0	3.4	83	4.3
T	−19.3	−15.5	−14.6	−9.6	−16.3	2.6	84	4.3

Rural region	UTCI (°C)	PET (°C)	AT (°C)	*T* (°C)	Tmrt (°C)	v_{10} (m·s^{-1})	*RH* (%)	*C* (octas)
UTCI	−24.4	−14.1	−13.6	−6.8	−12.1	5.5	82	5.5
PET	−21.8	−16.1	−15.0	−9.4	−15.9	3.5	82	4.2
AT	−22.2	−16.0	−15.1	−9.4	−15.7	3.7	82	4.4
T	−19.6	−15.8	−14.7	−9.6	−16.3	2.8	82	3.9

The rapid fall in UTCI due to wind speed in cold weather has been documented by Novák (Novák 2013). UTCI selects windy rather than freezing days in winter, and these show little effect on excess mortality among the urban population that is well protected against wind. However, windy winter weather with not extremely low air temperatures (but still far below 0 °C) may be related to more snowfalls (Spreitzhofer 1999) and therefore to diminished accessibility of small villages in the rural region, where the cold effect on mortality is most pronounced as indicated by UTCI. An analysis of relationships between cold days and the snowfalls in the two regions may help to explain the observed pattern, as there has been some evidence of a relationship between snowy weather and higher cardiovascular mortality (Kalkstein and Davis 1989). This relates, among other things, to physical exertion due to snow shovelling (Baker-Blocker 1982; Southern et al. 2006).

Our results extend previous findings (Burkart et al. 2011a; Kim et al. 2011; Nastos and Matzarakis 2011; Vaneckova et al. 2011) that air temperature (*T*), as the most widely used proxy for ambient thermal conditions in environmental epidemiology (Basu 2009; Ye et al. 2012), is a completely comparable tool to thermal indices in assessing heat-related mortality. However, insignificant (and substantially smaller compared to the other indices) cold-related mortality for *T* suggests that studies based on air temperature (including Urban et al. 2014) may be biased towards too-small estimates of cold effects. This finding is particularly important when the magnitude of changes in heat- and cold-related mortality associated with climate change in temperate regions is estimated (Gosling et al. 2009; Markandya and Chiabai 2009; Christidis et al. 2010).

Large differences on cold days as determined by UTCI, with excess mortality in the rural region but no effect in the urban region, suggest that UTCI may be less universal than other indices when applied in bioclimatic and epidemiological analyses (in which "average" thermal conditions for a population are used) as opposed to small-scale biometeorological studies with more specific meteorological input data. However, an influence of complex biometeorological conditions on human thermal comfort is indisputable, and human thermal comfort indices represent the thermal environment better than do simple empirical indices when proper input data are available (Błażejczyk et al. 2012). Nevertheless, human thermal comfort indices refer to an "average" healthy person, while the population groups most affected by thermal stress are elderly, young children and persons with impaired thermoregulation due to poor physical and medical condition (Cheng and Su 2010; Basu 2009; Mercer et al. 2002; Kenney and Munce 2003). According to Burkart et al. (2011a), the crucial question for the applicability of human thermal comfort indices to assessing epidemiological outcomes is the significance of the relationship between human health outcomes and the human heat balance. Moreover, the determination accuracy of human thermal comfort indices is affected by uncertainties in modelling mean radiant temperature (Tmrt). If all radiative fluxes are modelled based on synoptic observations (air temperature, air humidity, wind speed and cloudiness), the UTCI's uncertainties, which are due to uncertainties of the four meteorological input variables, may be as much as 6 °C (Weihs et al. 2012). This may cause inaccuracy in the thermal stress determination.

In addition to the aforementioned uncertainties in modelling of Tmrt, some other limitations need to be mentioned. Lacking appropriate data, we did not take into account demographic, socioeconomic and other environmental factors (e.g., air pollution) which are significant modifiers of weather-related mortality and should be considered in future research (Iñiguez et al. 2010; Burkart et al. 2011b; Hattis et al. 2012). Another limitation of this study is the use of airport station data in the analysis for the urban region. The station is situated at the airport on the north-western edge of Prague, which is colder and windier than the city centre, and hence the meteorological data may not be fully representative for the Prague population. Airport stations are often used in similar studies, however, and an analogous dataset from another Prague station was not available. Finally, since the lagged cold effect on mortality is still not wholly explained (Carder et al. 2005; Kyselý et al. 2009; Wichmann et al. 2011; Yu et al. 2012), we did not focus on analyzing lagged effects in this study. This issue needs to be elaborated in follow-up research.

3.5 Conclusions

We investigated the ability of UTCI and other thermal indices to identify discomfort days having adverse effects on patients with CVD in two regions of the Czech Republic. The results bring new insight to cold-related mortality assessment under temperate climatic conditions and to the applicability of thermal indices for estimating heat and cold effects in populations living in different environments (urban versus rural).

While similar heat effects for air temperature and thermal indices were found in both regions, differences in cold effects between individual indicators were much larger. In particular, UTCI selects windy winter days over the most freezing ones. That results in a small effect on excess mortality in the urban population that is sheltered from the effects of wind and, by contrast, the largest effect (among the examined indices) on excess mortality in the rural population. These findings raise also a critical issue as to the representativeness of wind speed measurements (taken at 10 m height above the surface and strongly determined by local conditions at the measuring site) for estimating human thermal discomfort, particularly in winter. While air temperature seems to be an appropriate tool for heat-related mortality assessment, it appears to be unsuitable when effect of cold on epidemiological outcomes is considered, and thermal indices (PET, AT) yield higher and probably more realistic cold-related mortality.

A universal indicator of human thermal comfort for various related disciplines (biometeorological forecasting, epidemiology, urban and regional planning, bioclimatic mapping, etc.) is desirable for easier comparison of results from different geographical areas and on different temporal and spatial scales. UTCI has the potential to become such a useful tool in human biometeorology (Błażejczyk et al. 2012; Jendritzky et al. 2012). However, AT (requiring only standard meteorological data) and PET appear to be more universal indicators in heat- and cold-related mortality assessments. Such findings need to be further investigated for other regions and populations, and they are important for determining the final procedure for cold exposure assessment within the UTCI calculation (Jendritzky et al. 2012; Schitzer et al. 2012).

Acknowledgements The study was supported by the Czech Science Foundation, project P209/11/1985. Thanks are due to B. Kříž and J. Kynčl, National Institute of Public Health, and H. Davídkovová, Institute of Atmospheric Physics AS CR, for preparing epidemiological and meteorological datasets as well as for useful discussions concerning their interpretation. In addition, thanks go to A. Matzarakis, University of Freiburg, for kindly providing the RayMan Pro software, and to anonymous reviewers that helped improve the original manuscript. Data were provided by the Institute of Health Information and Statistics, the Czech Statistical Office, and the Czech Hydrometeorological Institute.

Author Contributions Both authors contributed to the conception and design of the study, acquisition, analysis and interpretation of the data, and writing and revising of the manuscript. Aleš Urban carried out most statistical analyses and drafted the manuscript. Both authors approved the final version submitted for publication.

Conflicts of Interest The authors declare no conflict of interest

3.6 References

Basu R (2009) High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environ Health* 8: 40.

Bañuelos-Ruedas F, Camacho CÁ (2011) Methodologies used in the extrapolation of wind speed data at different heights and its impact in the wind Energy resource assessment in a region. In: Suvire, G.O. (eds.) *Wind Farm – Technical regulations, Potential Estimation and Siting Assessment*. 234 pp. ISBN 978-953-307-483-2, DOI: 10.5772/673. Available online: http://www.intechopen.com/books/wind-farm-technical-regulations-potential-estimation-and-siting-assessment. Accessed on 25 October 2013.

Baker-Blocker A (1982) Winter weather and cardiovascular mortality in Minneapolis-St. Paul. *Am J Public Health* 72: 261–265.

Blatecká K (2006) *The Basic Characteristics of Czech rural areas*. Diploma thesis. Masaryk University Brno (in Czech, with summary in English). http://is.muni.cz/th/137827/esf m/Diplomova prace.pdf. Accessed on 14 August 2013.

Błażejczyk K, Epstein Y, Jendritzky G, et al. (2012) Comparison of UTCI to selected thermal indices. *Int J Biometeorol* 56: 515–535.

Bröde P, Fiala D, Błażejczyk K, et al. (2012) Deriving the operational procedure for the Universal Thermal Climate Index (UTCI). *Int J Biometeorol* 56: 481–94.

Burkart K, Schneider A, Breitner S, et al. (2011a) The effect of atmospheric thermal conditions and urban thermal pollution on all-cause and cardiovascular mortality in Bangladesh. *Environ Pollut* 159: 2035–43.

Burkart K, Khan MH, KrämerA, et al. (2011b) Seasonal variations of all-cause and cause-specific mortality by age, gender, and socioeconomic condition in urban and rural areas of Bangladesh. *Int J Equity Health*, 10: 32.

Carder M, McNamee R, Beverland I, et al. (2005) The lagged effect of cold temperature and wind chill on cardiorespiratory mortality in Scotland. *Occup Environ Med* 62: 702–710. doi: 10.1136/oem.2004.016394

Cheng X, Su H (2010) Effects of climatic temperature stress on cardiovascular diseases. *Eur J Intern Med* 21: 164–167. doi: 10.1016/j.ejim.2010.03.001

Christidis N, Donaldson GC, Stott PA (2010) Causes for the recent changes in cold- and heat-related mortality in England and Wales. *Clim Change* 102: 539–553. doi: 10.1007/s10584-009-9774-0

CZSO (2012) *Statistical yearbook 2011.* Czech Statistical Office. Available at: http://www.czso.cz/csu/2011edicniplan.nsf/publ/0001-11-2010. Accessed on 20 August 2012.

Fiala D, Psikuta A, Jendritzky G, et al. (2010) Physiological modeling for technical, clinical and research applications. *Front Biosci* S2:939–968

Gabriel KMA, Endlicher WR (2011) Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. *Environ Pollut* 159: 2044–2050. doi:10.1016/j.envpol.2011.01.016.

Gómez-Acebo I, Dierssen-Sotos T, Llorca J (2010) Effect of cold temperatures on mortality in Cantabria (Northern Spain): a case-crossover study. *Public Health* 124: 398–403. doi:10.1016/j.puhe.2010.03.025

Gosling SN, Lowe JA, McGregor GR, et al. (2009) Associations between elevated atmospheric temperature and human mortality: a critical review of literature. *Clim Change* 92(3–4): 299–341. doi: 10.1007/s10584-008-9441-x

Hajat S, Kovats RS, Lachowycz K (2007) Heat-related and cold-related deaths in England and Wales: who is at risk? *Occup Environ Med* 64: 93–100. doi: 10.1136/oem.2006.029017

Hattis D, Ogneva-Himmelberger Y, Ratick S (2012) The spatial variability of heat-related mortality in Massachusetts. *Appl Geogr* 33: 45–52. doi: 10.1016/j.apgeog.2011.07.008

Havenith G, Fiala D, Błazejczyk K, et al. (2012) The UTCI-clothing model. *Int J Biometeorol* 56: 461–70.

Höppe P (1999) The physiological equivalent temperature, a universal index for the biometeorological assessment of the thermal environment. *Int J Biometeorol*43: 71–5.

Iñiguez C, Ballester F, Ferrandiz J, et al. (2010) Relation between temperature and mortality in thirteen Spanish cities. *Int J Environ Res Public Health* 7: 3196–210.

Jendritzky G, Staiger H, Bucher K, et al. (2000) The Perceived Temperature: the method of the Deutscher Wetterdienst for the assessment of cold stress and heat load for the human body. Internet Workshop on Windchill, 03.–07. April 2000, hosted by the Meteorological Service of Canada

Jendritzky G, de Dear R, Havenith G (2012) UTCI--why another thermal index? *Int J Biometeorol* 56: 421–8.

Kalkstein S, Davis R (1989) Weather and human mortality: an evaluation of demographic and interregional responses in the united states. *Ann Assoc Am Geogr* 79: 44–64.

Kántor N, Unger J (2011) The most problematic variable in the course of human-biometeorological comfort assessment — the mean radiant temperature. *Cent Eur J Geosci* 3: 90–100.

Kenney WL, Munce TA (2003) Invited review: aging and human temperature regulation. *J Appl Physiol* 95(6): 2598–603.

Kim Y-M, Kim S, Cheong H-K, et al. (2011) Comparison of temperature indexes for the impact assessment of heat stress on heat-related mortality. *Environ Health Toxicol* 26: e2011009.

Kynčl J, Prochazka B, Goddard NL, et al. (2005) A study of excess mortality during influenza epidemics in the Czech Republic, 1982–2000. *Eur J Epidemiol* 20: 365–371. doi:10.1007/s10654-005-1067-y

Kyselý J, Pokorná L, Kynčl J, et al. (2009) Excess cardiovascular mortality associated with cold spells in the Czech Republic. *BMC Public Health* 9: 19. doi: 10.1186/1471-2458-9-19

Laschewski G, Jendritzky G (2002) Effects of the thermal environment on human health: an investigation of 30 years of daily mortality data from SW Germany. *Clim Res* 21: 91–103. doi: 10.3354/cr021091

Markandya A, Chiabai A (2009) Valuing climate change impacts on human health: empirical evidence from the literature. *Public HealthInt J Environ Res Public Health* 6: 759–86.

Matzarakis A, Mayer H, Iziomon MG (1999) Applications of a universal thermal index: physiological equivalent temperature. *Int J Biometeorol*43: 76–84.

Matzarakis A, Muthers S, Koch E (2010a) Human biometeorological evaluation of heat-related mortality in Vienna. *Theor Appl Climatol* 105: 1–10. doi: 10.1007/s00704-010-0372-x

Matzarakis A, Rutz F, Mayer H (2007) Modelling radiation fluxes in simple and complex environments–application of the RayMan model. *Int J Biometeorol* 51: 323–34.

Matzarakis A , Rutz F, Mayer H (2010b) Modelling radiation fluxes in simple and complex environments–basics of the RayMan model. *Int J Biometeorol* 54: 131–139.

McGregor GR (2011) Human biometeorology. *Prog in Phys Geogr* 36(1): 93–109.

Mayer H, Höppe P (1987) Thermal comfort of man in different urban environments. *Theor Appl Climatol* 38: 43–49.

Medina-Ramón M, Schwartz J (2007) Temperature, temperature extremes, and mortality: a study of acclimatization and effect modification in 50 United States cities. *Occup Environ Med* 64: 827–833. doi: 10.1136/oem.2007.033175

Mercer JB (2002) Cold – an underrated risk factor for health. *Environ Res Environ Res* 92: 8–13. doi: 10.1016/S0013-9351(02)00009-9

Nastos PT, Matzarakis A (2011) The effect of air temperature and human thermal indices on mortality in Athens, Greece. *Theor Appl Climatol* 108: 591–599.

Novák M (2013) Use of the UTCI in the Czech Republic. *Geogr Pol* 86: 21–28.

Schoenberg, BS (1983) Calculating confidence intervals for rates and ratios. *Neuroepidemiology* 2: 257–265.

Shitzer A, Tikuisis P (2012) Advances, shortcomings, and recommendations for wind chill estimation. *Int J Biometeorol* 56: 495–503.

Smoyer KE, Kalkstein LS, Greene JS, et al. (2000) The impacts of weather and pollution on human mortality in Birmingham, Alabama and Philadelphia, Pennsylvania. *Int J Climatol* 20: 881–897.

Southern DA, Knudtson ML, Ghali WA (2006) Myocardial infarction on snow days: Incidence, procedure use and outcomes. *Can J Cardiol* 22: 59–61.

Spiezia V (2003) Measuring regional economies. Statistics Brief OECD, No. 6, October 2003. http://www.oecd.org/dataoecd/2/15/15918996.pdf. Accessed on 14 August 2013.

Spreitzhofer G (1999) Synoptic classification of severe snowstorms over Austria. *Met Z* 8: 3–15.

Steadman RG (1984) A universal scale of apparent temperature. *J Appl Meteorol Climatol* 23: 1674–1687.

Steadman RG (1994) Norms of apparent temperature in Australia. *Aust Met Mag* 43: 1–16.

Staiger H, Laschewski G, Grätz A (2012) The perceived temperature - a versatile index for the assessment of the human thermal environment. Part A: scientific basics. *Int J Biometeorol* 56: 165–76. doi: 10.1007/s00484-011-0409-6

Urban A, Davídkovová H, Kyselý J (2014) Heat- and cold-stress effects on cardiovascular mortality and morbidity among urban and rural populations in the Czech Republic. *Int J Biometeorol* doi: 10.1007/s00484-013-0693-4.

Vaneckova P, Neville G, Tippett V, et al. (2011) Do biometeorological indices improve modeling outcomes of heat-related mortality? *J Appl Meteorol Climatol* 50: 1165–1176. doi: 10.1175/2011JAMC2632.1

Weihs P, Staiger H, Tinz B, et al. (2012) The uncertainty of UTCI due to uncertainties in the determination of radiation fluxes derived from measured and observed meteorological data. *Int J Biometeorol* 56: 537–555.

Whitman S, Good G, Donoghue ER, et al. (1997) Mortality in Chicago attributed to the July 1995 heat wave. *Amer J Pub Health* 87: 1515–1518.

Wichmann J, Andersen ZJ, Ketzel M, et al. (2011) Apparent temperature and cause-specific mortality in Copenhagen, Denmark: a case-crossover analysis. *Int J Environ Res Public HealthPublic Health* 8: 3712–27.

Ye X, Wolff R, Yu W, et al. (2012) Ambient temperature and morbidity: a review of epidemiological evidence. *Environ Health Perspect* 120: 19–28. doi: 10.1289/ehp.1003198

Yu, W, Mengersen, K, Wang, X, et al. (2012) Daily average temperature and mortality among the elderly: a meta-analysis and systematic review of epidemiological evidence. *Int J Biometeorol* 56: 569–81.

4 Spatial patterns of heat-related cardiovascular mortality in the Czech Republic

Aleš Urban [1,2], Katrin Burkart [3], Jan Kyselý [1,4,5], Christian Schuster [6], Eva Plavcová [1], Hana Hanzlíková [1,7], Petr Štěpánek [5,8] and Tobia Lakes [6]

[1] *Institute of Atmospheric Physics, Czech Academy of Sciences, Boční II 1401, 14131 Prague 4, Czech Republic; kysely@ufa.cas.cz (J.K.); plavcova@ufa.cas.cz (E.P.); hanzlikova@ig.cas.cz (H.H.)*

[2] *Faculty of Science, Charles University, Albertov 6, 12843 Prague 2, Czech Republic*

[3] *Department of Environmental Health Science, Mailman School of Public Health, Columbia University, 722 W 168th Street, New York, NY 10032, USA; kgb2117@cumc.columbia.edu*

[4] *Faculty of Environmental Sciences, Czech University of Life Sciences, Kamýcká 129, 16521 Prague 6, Czech Republic*

[5] *Global Change Research Centre, Czech Academy of Sciences, Bělidla 986, 60300 Brno, Czech Republic; petrstep2@gmail.com*

[6] *Department of Geography, Geoinformation Science lab, Humboldt-Universität zu Berlin, Unter den Linden 6, 10099 Berlin, Germany; christian.schuster@hu-berlin.de (C.S.); tobia.lakes@geo.hu-berlin.de (T.L.)*

[7] *Institute of Geophysics, Czech Academy of Sciences, Boční II 1401, 14131 Prague 4, Czech Republic*

[8] *Czech Hydrometeorological Institute, Regional Office Brno, Kroftova 2578, 61667 Brno, Czech Republic*

Academic Editor: Jan Semenza

Abstract: The study examines spatial patterns of effects of high temperature extremes on cardiovascular mortality in the Czech Republic at a district level during 1994–2009. Daily baseline mortality for each district was determined using a single location-stratified generalized additive model. Mean relative deviations of mortality from the baseline were calculated on days exceeding the 90th percentile of mean daily temperature in summer, and they were correlated with selected demographic, socioeconomic, and physical-environmental variables for the districts. Groups of districts with similar characteristics were identified according to socioeconomic status and urbanization level in order to provide a more general picture than possible on the district level. We evaluated lagged patterns of excess mortality after hot spell occurrences in: (i) urban areas *vs.* predominantly rural areas, and (ii) regions with different overall socioeconomic level. Our findings suggest that climatic conditions, altitude, and urbanization generally affect the spatial distribution of districts with the highest excess cardiovascular mortality, while socioeconomic status did not show a significant effect in the analysis across the Czech Republic as a whole. Only within deprived populations, socioeconomic status played a relevant role as well. After taking into account lagged effects of temperature on excess mortality, we found that the effect of hot spells was significant in highly urbanized regions, while most excess deaths in rural districts may be attributed to harvesting effects.

Keywords: heat stress; mortality; socioeconomic status; spatial differences; cardiovascular disease

4.1 Introduction

Harmful effects of high atmospheric temperature on human health and lives have been documented in mid-latitudes (Basu 2009; Gosling et al. 2009a) as well as in tropical climates (Hajat and Kosatsky 2010; Burkart et al. 2014). Due to the rise in temperature with climate change, increased frequency and magnitude of extreme heat events are projected for the

21st century in comparison to recent climatic conditions (Gosling et al. 2009b; Ballester et al. 2009; IPCC 2014). Therefore, increased heat-related mortality is expected in future (Gosling et al 2009a; Huang et al. 2011). On the other hand, studies have documented declining impact of heat waves in developed countries due to behavioural and technological adaptation (Matzarakis et al. 2010; Kyselý and Plavcová 2011; Bobb et al. 2014), including more effective public warning and response (Toloo et al. 2013). Therefore, uncertainty in the projection of temperature-related mortality is still large (Gosling et al. 2009a; Huang et al. 2011; Gosling et al. 2012; Boeckamann and Rohn 2014).

Young children, the elderly and persons in poor physical and medical condition (Mercer 2002; Kenney and Munce 2003), and especially those with cardiovascular and respiratory diseases, are most affected by heat stress (McMichael et al. 2006; Basu 2009; Cheng and Su 2010). In the Czech Republic, excess all-cause and cardiovascular mortality due to hot conditions have been observed in several studies that considered the population as a whole (Kyselý and Huth 2004; Kyselý and Kříž 2008). The elderly, women and people with chronic cardiovascular diseases (CVDs) were found to be the populations groups with the largest heat-related mortality (Kyselý et al. 2011; Davídkovová et al. 2014; Hanzlíková et al 2015).

Many studies have investigated the effects of heat waves on urban populations, which are those most affected by heat-related mortality (Hajat 2007; Tan et al. 2010; Gabriel and Endlicher 2011). A higher percentage of elderly, socially deprived and isolated populations (people living alone, immigrants, ethnic minorities) have been identified as factors increasing heat-related mortality (Uejio et al. 2011; Hondula et al. 2012; Klein Rosenthal et al. 2014). In addition to socioeconomic factors, such land cover characteristics as the amount of impervious surface, green space, and unvegetated areas in the neighbourhood have been associated with increased heat vulnerability (Uejio et al. 2011; Reid et al. 2009; Reid et al. 2012; Bao et al. 2015) and heat-related mortality (Klein Rosenthal et al. 2014; Xu et al. 2013; Burkart et al. 2015). Heat stress has nevertheless been found to be a significant risk also for the rural population (Uejio et al. 2011; Sheridan et al. 2003; Maier et al. 2014; Kovach et al. 2015). Analyses in the Czech Republic have revealed comparably short-term response of cardiovascular mortality in both urban and rural population regardless of what temperature measure was used (Urban et al. 2014; Urban and Kyselý 2014). Spatial patterns in temperature-health relationships taking socioeconomic and environmental factors into account have not yet been investigated in the Czech Republic, however.

During heat waves, excess mortality often occurs for several days which are then followed by a decrease of mortality rates to below expected levels (so-called "mortality displacement" or "harvesting"; (Huynen et al. 2001; Kyselý 2004; Gosling et al. 2007). Although magnitudes of the short-term mortality displacement have been observed to vary considerably among populations of different cities (Basu 2009; Gosling et al. 2007; Baccini et al. 2013; Saha et al. 2014; Zaninović and Matzarakis 2014), studies assessing spatial variability in heat-related mortality according to urban *vs.* rural and socioeconomic differences in a specific geographic area do not usually address the harvesting issue (including Urban et al. 2014; Urban and Kyselý 2014).

In this study, we investigate spatial as well as temporal patterns for the effects of high temperature extremes on cardiovascular mortality in the Czech Republic at a district level. Effects of demographic, socioeconomic, and physical–environmental factors on excess cardiovascular mortality in 76 administrative districts are identified. Groups of districts with similar characteristics are compared in order to provide a more general picture and to evaluate different temporal patterns of excess mortality after hot spell occurrence in (i) urban areas *vs.* predominantly rural areas, and (ii) regions with different overall socioeconomic level.

4.2 Data and methods

4.2.1 Study area

The Czech Republic is a Central European country with a temperate climate and relatively varied landscape (Figure 4.1). Its approximately 10.2 million total inhabitants (as of 2001, with only minor changes during 1994–2009) are distributed into 77 districts (*Nomenclature of Units for Territorial Statistics* level 4 (NUTS 4) according to EUROSTAT (2015)), ranging from 42,000 inhabitants in the Jeseník District to about 1.2 million inhabitants in the capital city of Prague. While our mortality data start in 1994, the Jeseník District (CZ0711—Czech Statistical Office coding (CZSO 2004)) was established in 1996 by its separation from the Šumperk District. In order to retain homogeneity in mortality data, we considered Jeseník and Šumperk as a single district in our study (CZ0715). Thus, we analysed 76 districts.

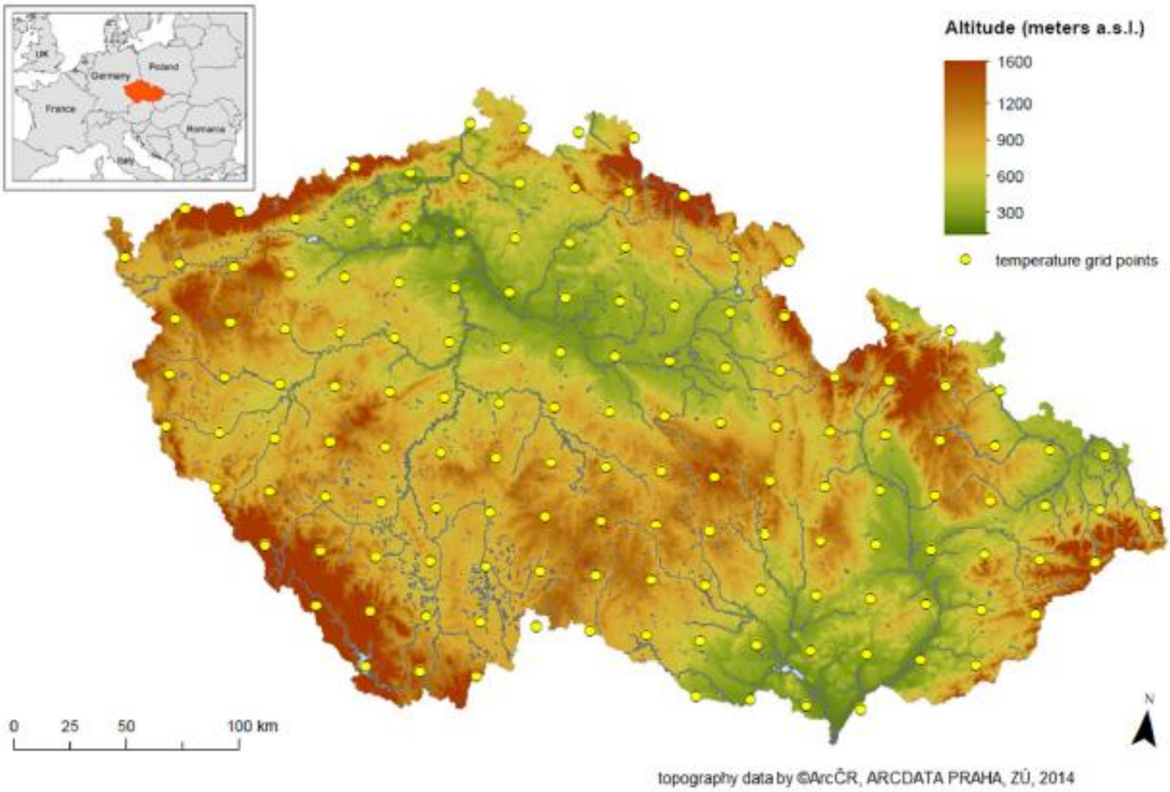

Figure 4.1 Topography of the Czech Republic (Digital Elevation Model provided by ARCDATA PRAHA) and distribution of regular temperature grid points (GriSt data set as described in Kyselý and Plavcová 2010).

4.2.2 Meteorological data

We considered average daily temperature in each district as a proxy variable for ambient thermal conditions. For its calculation, we used a high-resolution regular temperature grid covering the whole of the Czech Republic (see Figure 4.1). The GriSt data set with resolution 25 × 25 km is based on interpolated mean daily temperature data from irregularly spaced meteorological stations operated by the Czech Hydrometeorological Institute as described in Kyselý and Plavcová (2010). Such data were not available for other meteorological variables needed as inputs for calculating biometeorological indices (see Błażejczyk et al. 2012). Every grid box provides information about mean daily temperature from 1 January 1994 to 31 December 2009 and average altitude. Total population in each grid box in 2001 was calculated from the Gridded Population of the World (v3) (GPW 2005). Finally, the average daily temperature in each district was calculated from grids falling into the district area weighted by population within these grids (Figure 4.2). Average altitude of grids falling into each district was calculated as well. Zonal statistics tools in QGIS Desktop 2.4.0 were used for transformation of the grid data to districts.

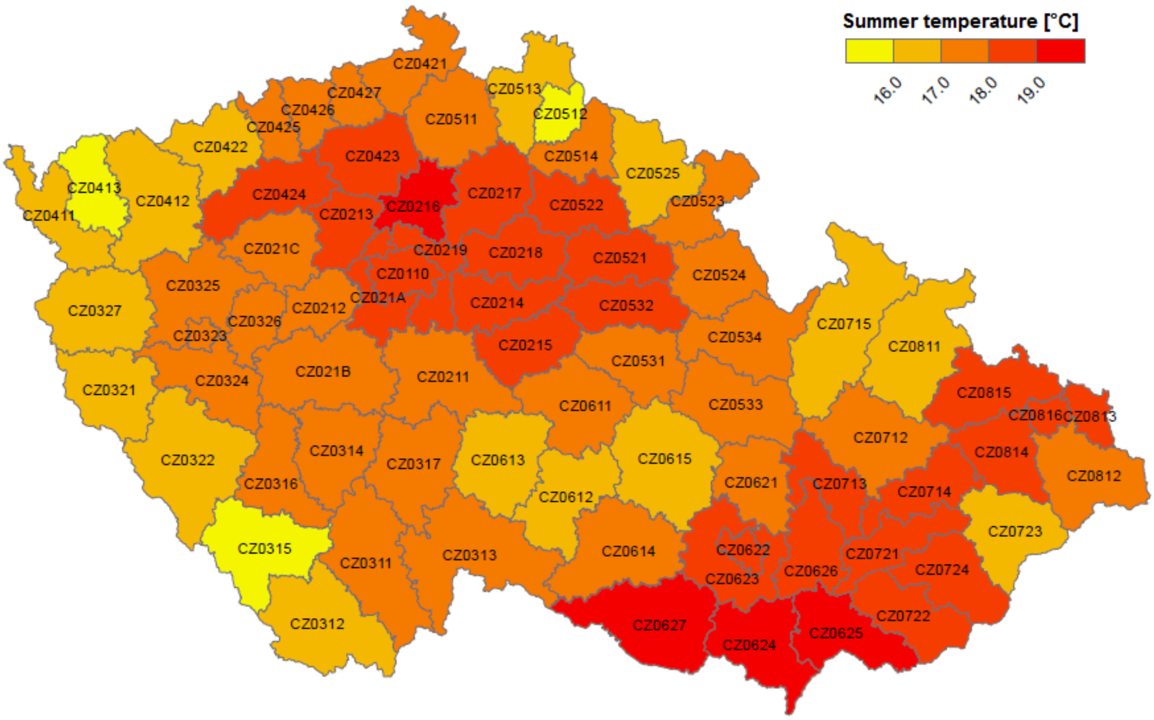

Figure 4.2 Average summer temperature (June–August 1994–2009) in districts of the Czech Republic calculated from the GriSt data set. Districts are labelled according to the Czech Statistical Office coding (CZSO 2004).

4.2.3 Mortality data

We analysed daily mortality from cardiovascular diseases (CVDs; defined as codes I00–I99 according to the International Statistical Classification of Diseases, 10th Revision [ICD-10]) in each district during 1994–2009. Mortality from CVDs comprises more than 50% of total mortality in the Czech Republic with a total record of 930,659 deaths occurring during the study period (Davídkovová et al. 2013). As the population count and structure vary distinctly between districts, daily mortality rates were calculated by the direct standardization procedure, using the mid-year population of each district in the Czech Republic and the standard WHO European population as the standard (Ahmad et al. 2001). Daily baseline mortality for individual districts was determined using a single location-stratified generalized additive model ("mgcv" package in R (version 2.15.2); Wood 2006). A spline function with seven degrees of freedom (df) per year (total df = 112) was used according to Bhaskaran et al. (2013), in order to take account for long-term trend and seasonality. Additional components taking account for the day of week and the district were defined by categorical variables. Mean relative deviations of mortality from the baseline (excess mortality) on days with average temperature above the 90th percentile (hot days) in summer seasons (June–August) 1994–2009 were calculated for all districts (*DevCVD*). The 90th percentile instead of the 95th percentile was chosen because it yields larger sample size, which is beneficial for the analysis at district level. Statistical significance of mean relative deviations was evaluated by comparison with the 90% confidence bounds around the zero line, estimated from the 5% and 95% quantiles of a distribution calculated by the Monte Carlo method (cf. Plavcová and Kyselý 2010). Spatial autocorrelation of mortality deviations on all summer days as well as on hot days was tested by Global Moran's *I* criteria (Getis and Ord 1992) in ArcGIS 10 software.

4.2.4 Analysis of spatial patterns of heat-related mortality

We used demographic and socioeconomic characteristics from the Census 2001 database (provided by the Czech Statistical Office), land cover characteristics from the CORINE land cover 2000 database (the Czech Environmental Information Agency), and mean summer temperature (*summer T*) and mean *altitude* calculated from the GriSt data set in order to identify effects of demographic, socioeconomic, and physical–environmental factors on spatial differences in heat-related mortality. The selection of demographic and socioeconomic variables was based on a literature review (Reid et al. 2009; Vescovi et al. 2005; Wichmann et al. 2011; Hattis et al. 2012; Harlan et al. 2013) and adapted with respect to the limitations of the Census database. We applied a modified population density variable according to the OECD's international terminology (Spiezia 2003) (hereafter termed *OECD* criterion) which defines a level of urbanization by percentage of inhabitants living in municipalities with population density less than 150 inhabitants per 1 km^2. An index of socioeconomic status (*SES*) for each district was calculated as a sum of *z*-scores for 3 factors of social deprivation related to elevated mortality in the Czech Republic (Šplíchalová et al. 2007). Percentages of unemployed population (*% unemployed*), people without secondary school diploma (*% low education*), and single-person households (*% singles*) were included into the index. The final index is a dimensionless variable with a range between 2.66 (highest *SES*) and −5.88 (lowest *SES*) across the districts in the Czech Republic.

Land cover structure of each district was calculated using zonal statistics tools in QGIS Desktop 2.4.0. Percentage of impervious surface (*% impervious*) representing residential, industrial, commercial and transport areas was chosen similarly to other studies as a land cover variable enhancing heat stress (Uejio et al. 2011; Hondula et al 2012; Johnson et al. 2012; Harlan et al. 2013; Klein Rosenthal et al. 2014; Maier et al. 2014; Kovach et al. 2015). The specific list of all variables used is presented in Table 4.1. Spearman's correlation coefficients (and their *p*-values) of relationships between mean relative mortality deviations on hot days and independent variables were calculated using the "rcorr" function in the R package "Hmisc" (version 3.14-3) (Harrell et al. 2004). To check for multicollinearity between explanatory variables, we used variance inflation factors (VIFs) calculated in the ordinary least squares (OLS) regression in ArcGIS. If two or more explanatory variables had a large VIF (>7.5), the variable leading to the OLS regression model with lower percentage of variance explained was excluded from further analysis. After reduction of variables, we performed a bidirectional stepwise regression procedure testing all remaining explanatory variables, in order to identify the most significant variables affecting excess CVD mortality due to heat. The "stepAIC" function in the "MASS" package in R (version 2.15.2) adds or drops variables to or from the model repeatedly, fits those models, and computes a table of the changes in fit according to the Akaike information criterion (AIC) and amount of variance explained (Venables 2002), i.e., the model with the lowest AIC and all significant parameters (as determined by an F test, $p < 0.05$) was selected. Spatial autocorrelation of the model residuals was evaluated with Global Moran's I criteria. Ultimately, linear relationships of CVD mortality deviations with independent variables representing socioeconomic status (*SES*), population density (*OECD* criterion), and environmental effects (*summer T*) were examined individually for districts with *low* (<−0.50 StdDev), *intermediate*, and *high* (>0.50 StdDev) *SES*.

Table 4.1 District characteristics tested in the analysis.

Variable	Description
DevCVD	Mean relative CVD mortality deviations on hot days with average temperature above the 90th percentile in June–August 1994–2009
SES	Index of socioeconomic status; sum of z-scores for % low education, % unemployed and % singles
% elderly	% of population older than 65 years
% low education	% of population without secondary school diploma
% unemployed	% of unemployed population
% singles	% of single-person households
OECD	% of inhabitants in municipalities with population density less than 150 inhabitants/km^2
Summer T (°C)	Mean summer (1 June–31 August 1994–2009) temperature in °C
Altitude (m a.s.l.)	Average altitude in metres above sea level
% impervious	% of impervious surface area (categories 1.1 and 1.2 in the CORINE land cover classification)

4.2.5 *Analysis of temporal patterns of heat-related mortality in groups of districts*

Groups of districts with similar characteristics were defined in order to obtain greater population sample sizes and provide a more general picture of results on the district level. The districts with *high SES* and *low SES* were split into *urban* (*OECD* < 25%) and *rural* (*OECD* > 37.5%) districts according to the *OECD* criterion of the population density calculated for the Czech Republic by Blatecká (2006). Mortality rates and temperature data of all districts in each of the four groups (*high SES-Urban*, *high SES-Rural*, *low SES-Urban*, and *low SES-Rural*) were averaged and baseline mortality for each group using the same GAM formula as for individual districts was again calculated. The four *groups of districts* are displayed in Figure 4.3 and their characteristics are presented in Table 4.2.

Table 4.2 Total population and average demographic, socioeconomic, and physical–environmental characteristics (in 2001) of the four *groups of districts* presented in Figure 4.3.

Characteristic	High SES-Urban	High SES-Rural	Low SES-Rural	Low SES-Urban
Population	1,871,095	1,197,212	694,115	1,170,971
OECD	5.93	48.95	50.88	10.51
SES	2.06	1.56	−1.85	−3.62
% elderly	15.56	13.91	12.20	11.94
% low education	49.67	65.08	68.59	65.73
% unemployed	3.81	3.15	6.64	8.16
% singles	33.82	27.01	29.23	33.54
Summer T (°C)	18.4	17.4	17.6	17.5
Altitude (m a.s.l)	327	459	392	415
% impervious	29.82	4.45	4.40	13.42

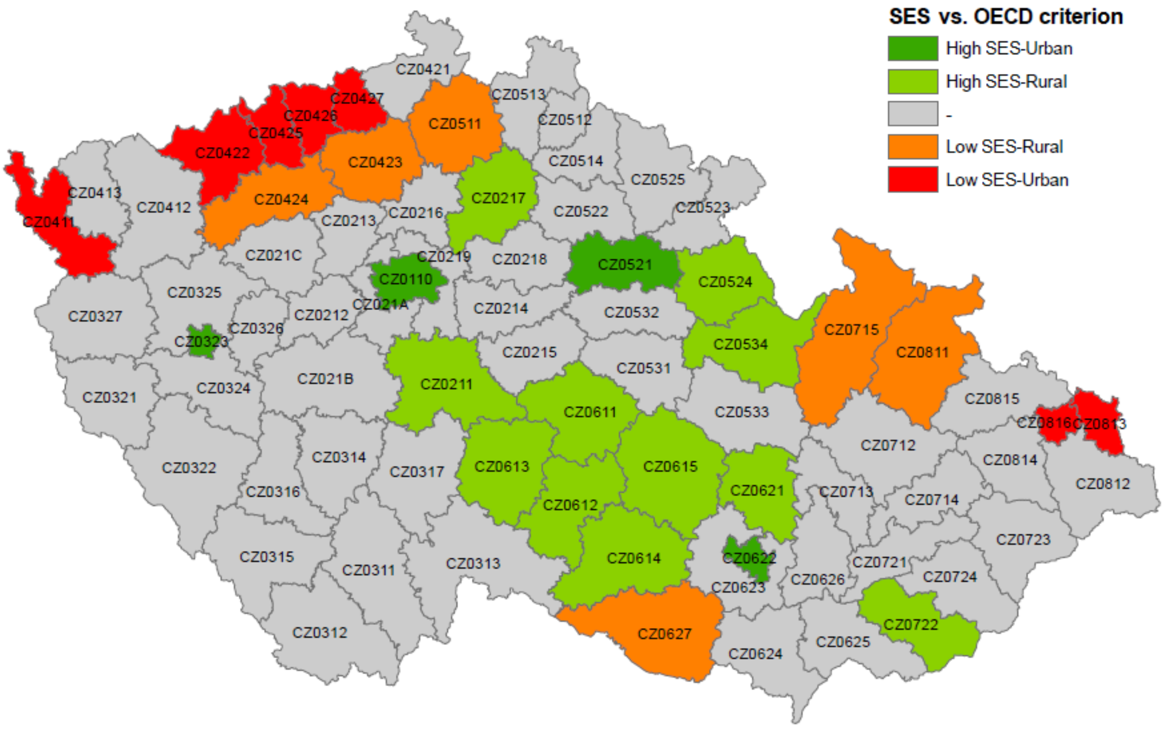

Figure 4.3 Four *groups of districts* identified according to *high* (>0.50 StdDev) and *low* (<−0.50 StdDev) index of socioeconomic status (*SES*) and *urban* (*OECD* criterion <25%) and *rural* (*OECD* criterion > 37.5%) population.

Hot spells were defined as at least two consecutive days with average temperature above the 90th percentile of its distribution in summer seasons (June–August) 1994–2009 in a given *group of districts*. A percentile definition was chosen because it leads to similar numbers of days in hot spells in each group of districts. Relative deviations of CVD mortality from the baseline on days D − 2 (2 days before the beginning of a hot spell) up to D + 14 were averaged over all hot spells in order to assess lagged patterns of mortality deviations. Statistical significance of mean relative deviations was evaluated by comparison with the 90% and 95% confidence bounds around the zero line, estimated from the 2.5%, 5%, 95%

and 97.5% quantiles of a distribution calculated by the Monte Carlo method (cf. Plavcová and Kyselý 2010). As the effect of a heat event on significantly elevated mortality usually occurs up to 3 days after the event (Basu 2009; Kyselý 2004; Kyselý and Huth 2004), cumulative excess CVD mortality on days D + 0 to D + 3 and D + 4 to D + 14 after a hot spell's onset was compared in order to estimate magnitude of the mortality displacement effect.

4.3 Results

4.3.1 Heat-related mortality in the Czech Republic at district level

About 148 hot days were defined in each district during 1994–2009. The highest and statistically significant ($p < 0.1$) heat-related mortality (*DevCVD*) was generally experienced in the northwest and southeast Czech Republic and in large municipalities (Prague-code CZ0110, Pilsen-CZ0323, Brno-CZ0622, Ostrava-CZ0816; Figure 4.4). These areas are mostly located in the lowest and warmest parts of the Czech Republic (cf. Figures 4.1 and 4.2). However, the test for spatial autocorrelation (Global Moran's *I*) did not show any significant spatial clustering of mean mortality deviations on all summer days as well as on hot days.

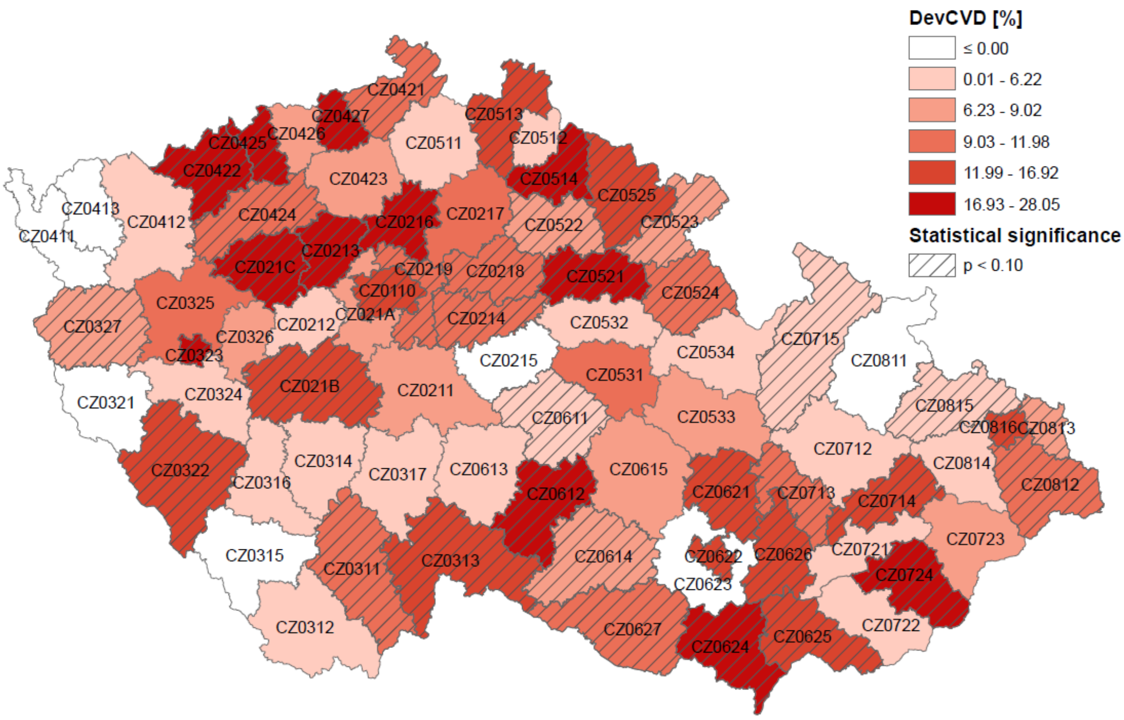

Figure 4.4 Spatial distribution of mean relative mortality deviations due to CVDs on hot days (*DevCVD*). Districts are labelled according to the Czech Statistical Office coding (CZSO 2004).

4.3.2 Explaining Spatial Patterns of Heat-Related Mortality

Spearman's correlation analysis revealed generally very weak and insignificant correlation of relative CVD mortality deviations (*DevCVD*) with most of the socioeconomic factors (Table 4.3). On the contrary, variables representing effects of physical environment and urbanization level (altitude, *summer T*, and *%* impervious) correlated significantly (*p* <

0.05) with mortality anomalies on hot days (r = 0.37, −0.37, and 0.34 respectively), although correlation coefficients for the significant variables were still rather weak. Variables correlating significantly with mortality deviations correlated also significantly with one another. In particular, *altitude* and *summer T* showed strong negative correlation (r = −0.92). These two variables were also associated with large VIFs (>7.5) which indicates their strong collinearity. Since *summer T* led to higher percentage of variance explained, *altitude* was excluded from the regression analysis.

Table 4.3 Spearman's correlation matrix comparing the mean relative excess mortality due to CVDs on hot days (*DevCVD*) with independent variables used in the analysis (see Table 1 for description). Significant coefficients with p-value < 0.05 are in bold.

Independent Variable	DevCVD	SES	% elderly	% low education	% unemployed	% singles	OECD	Summer T (°C)	Altitude (m a.s.l.)
SES	0.01	1							
% elderly	0.14	**0.61**	1						
% low education	−0.20	**−0.52**	**−0.47**	1					
% unemployed	0.12	**−0.75**	**−0.53**	**0.33**	1				
% singles	0.13	**−0.38**	−0.04	**−0.24**	0.09	1			
OECD	−0.22	0.11	0.07	**0.47**	**−0.24**	**−0.56**	1		
Summer T (°C)	**0.37**	0.18	**0.38**	−0.19	0.10	−0.08	−0.19	1	
Altitude (m a.s.l.)	**−0.37**	−0.05	**−0.31**	**0.17**	−0.13	−0.09	**0.26**	**−0.92**	1
% impervious	**0.34**	0.05	0.12	−0.41	**0.24**	0.23	**−0.74**	**0.64**	**−0.66**

The stepwise regression procedure identified district's *summer T* as the most significant factor positively linked to excess mortality (Table 4.4). The increased population density (decreased *OECD* criterion) was chosen by the model as the second variable significantly associated with increased mortality. Global Moran's *I* criteria close to 0 indicated no spatial autocorrelation of residuals from the stepwise regression model.

Table 4.4 Independent variables (see Table 4.1) chosen by the stepwise regression model as significantly related to the mean relative excess mortality due to CVDs on hot days (*DevCVD*) in individual districts. Regression coefficients are reported, along with their associated p-values in parentheses.

Independent Variable	DevCVD
SES	----
% elderly	----
% low education	----
% unemployed	----
% singles	----
OECD	−0.096 (0.043)
Summer T (°C)	2.922 (0.002)
% impervious	----
R^2	0.191

In the analyses for all districts considered together, regression procedure did not reveal any significant effect of socioeconomic status (*SES*) on heat-related mortality (*DevCVD*). However, regression analysis between *DevCVD* and selected explanatory variables showed significant changes in the relationships (Table 4.5, Figure 4.5) when performed individually for districts with *low*, *intermediate* and *high SES*. In *high SES* districts, the decreased *OECD* criterion (*i.e.*, increased percentage of urban population) was the only variable significantly (p<0.1) linked to increase in *DevCVD*. In the largest group of districts with the *intermediate SES*, only increased *summer T* was significantly ($p < 0.05$) associated with increased *DevCVD*. But in districts with *low SES*, increased *DevCVD* was significantly ($p < 0.05$) linked to increased *summer T*, decreased *OECD* criterion as well as decreased *SES* (considered as explanatory variable). Decreased *SES* was also significantly related to a decrease of the *OECD* criterion in the same category.

Results obtained from the analysis at the district level gave us general information about spatial distribution of heat-related excess mortality due to CVDs. Although in most districts the mean mortality deviations were positive and significantly different from zero (Figure 4.4), numbers of cases especially in rural districts were rather low and baseline estimates in such districts were affected by overdispersion. Therefore, the districts were divided into *groups of districts* according to the *SES* index and the *OECD* criterion in order to compare effects of high temperature in larger population samples.

Table 4.5 Linear regression models for mean relative excess mortality due to CVDs on hot days (*DevCVD*) against index of socioeconomic status (*SES*), percentage of rural population (*OECD* criterion), and mean summer temperature (*Summer T*) for districts with *low*, *intermediate*, and *high* socioeconomic status (*SES* class). Regression coefficients are reported, along with their associated p-values in parentheses. See Table 4.1 for description of variables examined. Significant regression coefficients with p-value < 0.05 are in bold.

SES Class	DevCVD *vs.* SES	DevCVD *vs.* Summer T (°C)	DevCVD *vs.* OECD	SES *vs.* OECD
Low	**−3.099 (0.034)**	**4.307 (0.025)**	**−0.193 (0.044)**	**0.041 (0.000)**
Intermediate	−3.399 (0.490)	**3.537 (0.008)**	−0.073 (0.407)	0.008 (0.293)
High	1.474 (0.842)	1.234 (0.181)	−0.164 (0.078)	−0.008 (0.347)
R^2	0.086	0.160	0.107	0.878

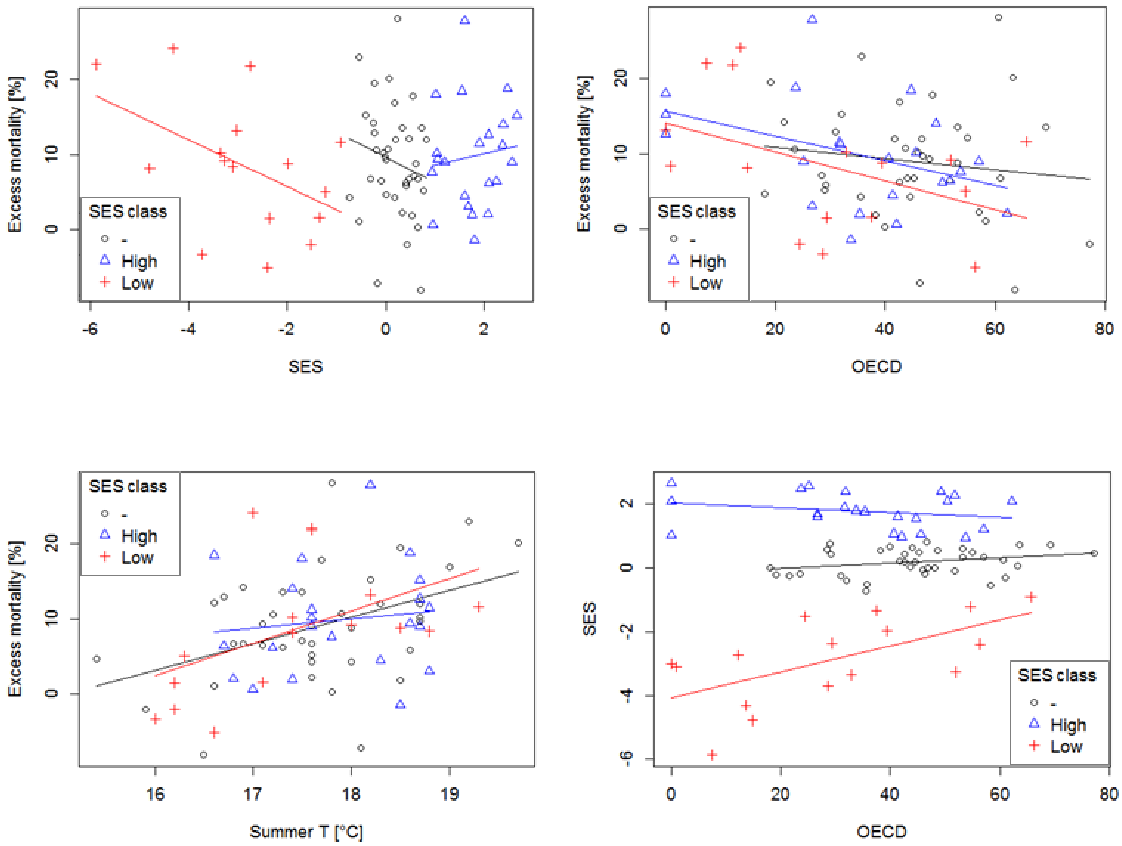

Figure 4.5 Scatterplots comparing mean relative excess mortality due to CVDs on hot days (*DevCVD*) with index of socioeconomic status (*SES*), percentage of rural population (*OECD* criterion), and mean summer temperature (*Summer T*) for districts with *low* (<−0.50 StdDev), *intermediate* (-), and *high* (>0.50 StdDev) socioeconomic status (*SES*). Coefficients of regression lines are reported in Table 4.5. See Table 4.1 for description of variables examined.

4.3.3 Explaining lagged patterns of heat-related mortality in groups of districts

About 35 hot spells were defined in each *group of districts* during 1994–2009. In all groups, significant excess mortality occurred between days D + 0 and D + 3 after a hot spell's onset followed by a decline in mortality deviations (Figure 4.6). While in rural districts the lagged mortality deviations (D + 4 and later) were predominantly negative, in urban districts they were rather positive during the whole two-week period after a hot spell's onset. When cumulative mortality deviations on days D + 0 to D + 3 and D + 4 to D + 14 after a hot spell's onset were compared (Figure 4.7), the immediate cumulative effect (ΣD + 0…D + 3) was largest in the most densely populated and the warmest *group of districts* with high socioeconomic status (*high SES-Urban*, 58.2% of daily mortality), while it was lowest in the least populated group with low socioeconomic status (*low SES-Rural*, 20.4%). When taking into account the lagged effects (ΣD + 4…D + 14), however, we observed negative relative mortality deviations in rural *groups of districts* which results in total heat-effects during the two-week period close to zero (8.9% and −3.8% in *high SES-Rural* and *low SES-Rural*, respectively). On the contrary, the cumulative lagged effects were positive in urban districts. In the urban district with low *SES* (*low SES-Urban*), the lagged effect was comparable with the immediate one (26.3%), while in the *high SES-Urban* group the additional increase in excess mortality was rather small (8.4%).

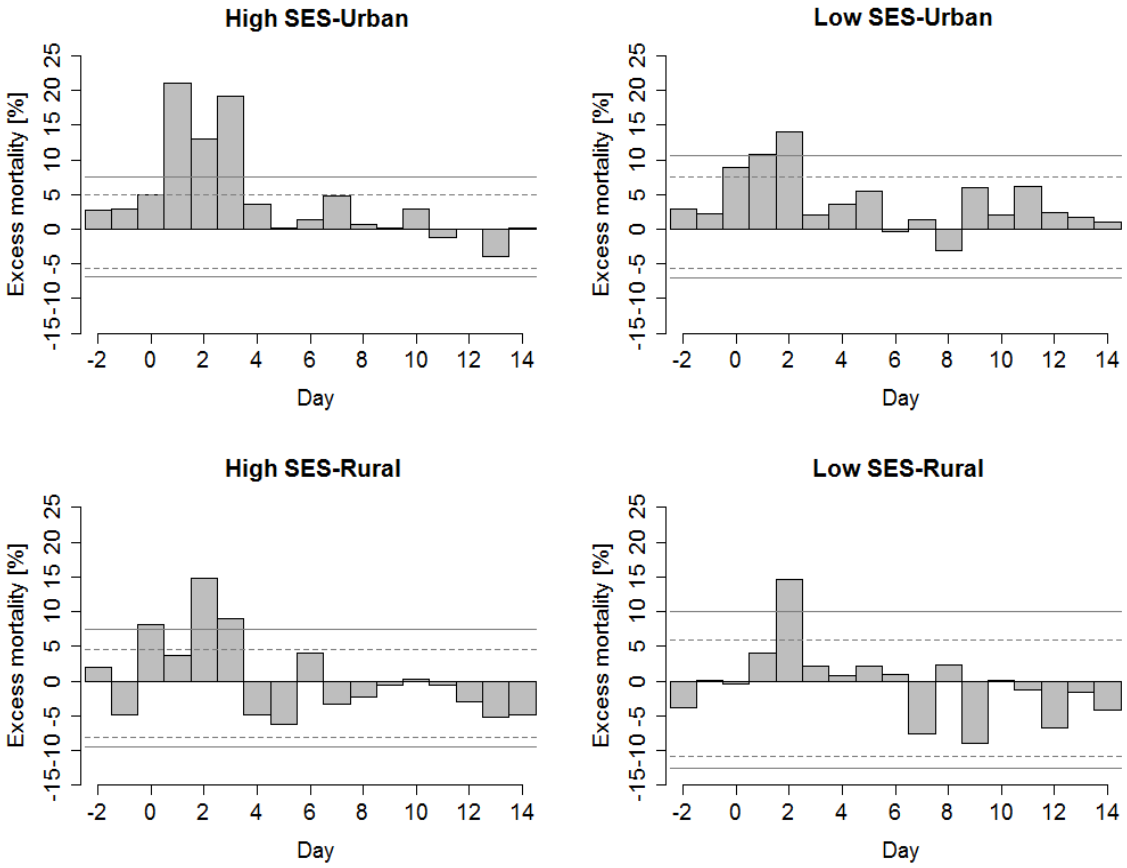

Figure 4.6 Mean relative excess mortality due to CVDs on days D − 2 to D + 14 around a hot spell's onset in the *groups of districts*. Confidence bounds around the zero line are indicated by *dashed* (90%) and *solid* (95%) lines, respectively.

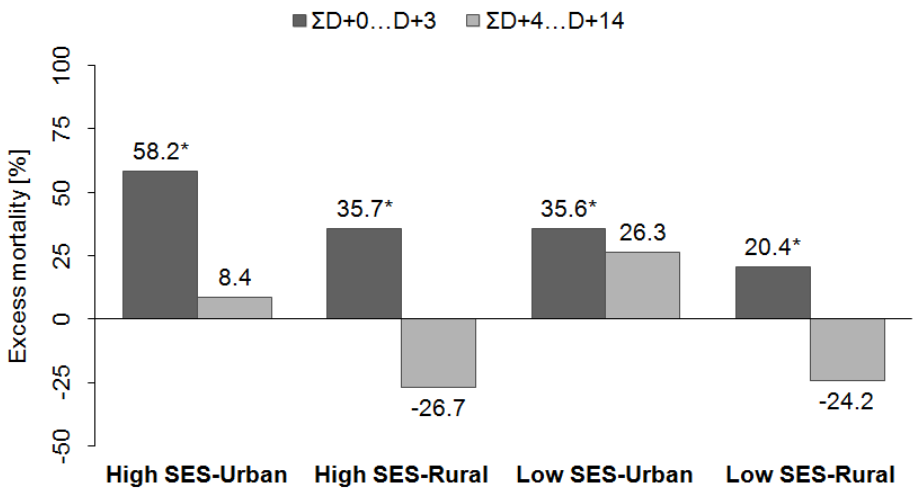

Figure 4.7 Cumulative excess mortality (relative to the daily baseline mortality) due to CVDs on days D + 0 to D + 3 (ΣD + 0…D + 3) and D + 4 to D + 14 (ΣD + 4…D + 14) after a hot spell's onset in the *groups of districts*. * denotes mean cumulative excess mortality above the 95% quantile of a distribution calculated by the Monte Carlo method.

4.4 Discussion

We analysed spatial and temporal patterns of links between daily CVD mortality and mean daily temperature during summer (June–August), 1994–2009 in the Czech Republic. We further evaluated these patterns with respect to demographic, socioeconomic, and physical-environmental differences. The largest relative mortality deviations on days that exceeded the 90th percentile of summer temperature distribution (hot days) were generally observed in the warmest and most densely populated regions of the Czech Republic.

4.4.1 Spatial patterns of heat-related mortality

When all districts in the Czech Republic were considered together, characteristics of physical environment (mean summer temperature, altitude) and urbanization level (population density, percentage of impervious surface) had a significant influence on heat-related CVD mortality, while socioeconomic status did not show any significant effect. On the other hand, a comparison of districts with low and high index of socioeconomic status (*SES*) revealed that below a certain threshold, *SES* has a relevant influence on excess mortality.

Although previous studies have demonstrated differences in the heat–health relationship between different cities and different population groups, there are only few studies including also rural areas and considering socioeconomic and land cover factors affecting spatial differences in heat-related mortality. In the U.S., Sheridan and Dolney (2003) found a comparable effect of heat on mortality in urban and rural counties in Ohio. In Massachusetts (Hattis et al. 2012) and Georgia (Maier 2014), demographic (percentage of elderly, percentage of African-Americans) and socioeconomic (social isolation, poverty) factors were more important than was the level of urbanization (as represented by population density and proportion of the impervious surface). Recently, Kovach et al. (2015) in North Carolina found greater rates of heat-related illnesses in rural than urban locations, and a greater proportion of workers in agriculture with less access to air conditioning has been mentioned among the reasons of high heat-vulnerability in rural populations (Sheridan and Dolney 2003; Kovach et al. 2015). On the other hand, decreased vegetation, living in poverty, and low education were associated with increases in heat-related illnesses in urban locations (Kovach et al. 2015). However, excess morbidity and mortality due to heat in U.S. cities is reduced by the protective effect of air conditioning (Sheridan and Dolney 2003; Medina-Ramón and Schwartz 2007). Air conditioning is much less widespread in Europe than in American households (Henderson 2005), and population in the most densely populated areas is usually most affected by heat in Europe (Hajat et al. 2007; Gabriel and Endlicher 2011). Moreover, in contrast to the U.S. and many western-European countries, social differences between urban, suburban and rural populations in the Czech Republic are much smaller, as the country ranks as having among the lowest income inequality of OECD countries (OECD 2015), and the lowest estimated percentage of population severely deprived with respect to health, education and/or standard of living in the European Union (the Human Poverty Index, HPI; Bubbico and Dijkstra 2011). In addition, none of the aforementioned studies considered the effects of physical–geographic conditions such as local climate and topography. Strong collinearity between districts' average temperature and altitude found in our results suggests that highest heat-related mortality is generally observed in districts with low altitude, relatively hotter local climate and higher level of urbanization. Nevertheless, the significant relationship between decreased socioeconomic status and increased heat-related mortality in the most deprived district group highlights the role of social deprivation in vulnerability to heat across the population of the Czech Republic.

4.4.2 Lagged Patterns of Heat-Related Mortality

Another limitation of many studies assessing spatial variability in heat-related mortality within specific geographic areas is that they do not take into account the mortality displacement (harvesting effect) issue. Analysis of the four *groups of districts* with larger sample sizes allowed us to study lagged patterns of mortality deviations with more statistical power than for individual districts. While in urban districts the lagged sums of mortality deviations were still positive, we observed large decreases in cumulative relative mortality deviations in rural districts. A decline in mortality a few weeks after a heat wave due to mortality displacement has been documented in many studies (Kyselý 2004; Gosling et al. 2007; Baccini et al. 2013; Saha et al. 2014; Zaninović and Matzarakis 2014). Although estimates of the mortality displacement magnitude vary based on the methodology used and between different populations (Basu 2009; Baccini 2013), our findings suggest that, at least in the Czech Republic, the effect of mortality displacement after hot spells is small and insignificant in urban districts, while most of the excess deaths in rural districts may be attributed to harvesting.

The highest short-term effect of hot spells in the *high SES-Urban* group suggests that high socioeconomic status was a risk factor of increased excess CVD mortality in the stratified analysis. However, the regression analysis at the district level showed *SES* as a relevant factor only in the *low SES* districts. Therefore, highest population count and density, highest average summer temperature due to low altitude, and generally worst thermal conditions in comparison to other *groups of districts* due to high proportion of artificial surface are probably the main reasons for the largest short-term effect of hot spells on excess CVD mortality in the *high SES-Urban* group. Many studies have documented strongest heat effects on mortality in the most densely populated areas (Hajat et al. 2007; Tan et al. 2010; Gabriel and Endlicher 2011) due to urban heat island effects (Arnfield 2003; Fisher et al. 2012), although this may be altered by large-scale factors such as altitude and topography (Alcoforado and Andrade 2006) as well as such fine-scale factors as proportions of impervious, green or water surfaces (Unger 2004; Dütemeyer et al. 2013; Dugord et al. 2014; Burkart et al. 2015).

Short-term heat effect was reduced in the urban *group of districts* with low socioeconomic status (*low SES-Urban*) in comparison to *high SES-Urban*. However, when the cumulative relative mortality deviations during the two-week period after a hot spell's onset were considered, excess CVD mortality in *low SES-Urban* was comparable with that in the *high SES-Urban* group (62% and 67%, respectively). This may be caused not only by relatively high levels of urbanization but also by social deprivation of populations in *low SES-Urban* districts, inasmuch as regression analysis at the district level had shown a significant relationship between socioeconomic status and heat-related CVD mortality for districts with low socioeconomic status. Dzúrová (1993) had demonstrated significant relationships between environmental deprivation, social deprivation, and poor health condition within the population of the Czech Republic. Long-term exposure to high concentrations of particulate matter (PM) has been associated with development of chronic diseases of the veins and heart (Brook et al. 2004; Chen and Goldberg 2009; Kaufmann 2010). People with chronic CVDs have been most affected by excess mortality during hot spells in the Czech Republic (Davídkovová et al. 2014; Urban et al. 2014). Highest concentrations of PM_{10} and O_3 have been associated with oppressive weather in Prague, although they were not identified as significant factors linked to excess CVD mortality by a stepwise regression model within the oppressive air masses (Urban and Kyselý 2015). Since heavy industry and coal mining are typical economic activities in districts of the *low SES-Urban* group, poor health condition due to long-term exposure to high air pollution concentrations (CHMI 2015) and in general highest environmental deprivation within the Czech Republic in these districts may have a significant effect on lagged excess mortality due to CVDs during hot spells. However, inasmuch as air pollution characteristics are not spatially representative because they vary considerably across space, and causal relationships among temperature, air pollution, and human health are associated with large uncertainty (Buckley et al. 2014), we did not consider the effect of air pollution in this study.

4.4.3 Limitations of the study

A usual issue of studies assessing spatial variability of weather-mortality relationships is to find a trade-off between geographic specificity and sample size when selecting a unit of analysis (Hattis et al. 2012). The length of time period (number of days) and number of events (e.g., deaths) per day are factors determining statistical power and precision of time series modelling (Bhaskharan et al. 2013). For example, Hondula and Barnett (2014) employed a hierarchical Bayesian model treating each unit as not completely independent from every other. We applied a single generalized additive model stratifying the whole dataset to individual districts by a categorical variable, which allowed us to model baseline mortality consistently in all districts and helped to deal with small population counts. Mortality deviations in individual districts are still subject to great uncertainty, as numbers of deaths in districts of the Czech Republic show high variability and only a small percentage of total variance can be explained by meteorological factors (Urban and Kyselý 2015). Therefore larger regions should be considered for heat-related mortality assessment and biometeorological forecast (e.g., Novák 2013) in the Czech Republic rather than individual districts.

Our findings also highlight the importance of relating heat risk factors to appropriate health variables when evaluating vulnerable populations and regions. This is an issue in particular for studies mapping heat vulnerability without validation on health outcomes (Reid et al. 2009; Vescovi et al. 2005; Johnson et al. 2012). As demonstrated by Reid et al. (2012), a heat vulnerability index calculated from socioeconomic and environmental risk factors can be consistently associated with poor health on both normal and hot days. In our study, low socioeconomic status (*SES*) was strongly correlated with high mortality (not shown), while the association with excess mortality on hot days was weak. Excess deaths during a heat wave can be considered as an extreme outcome of heat stress. Previous studies have revealed no significant effect of high temperatures on hospitalizations due to CVDs (Urban et al. 2014; Zacharias et al. 2014; Hanzlíková et al. 2015; Urban and Kyselý 2015). Nevertheless, health outcomes such as emergency calls (Uejio et al. 2011; Wolf et al. 2014) and hospital admissions for respiratory and heat-related diseases (Reid et al. 2012; Scherber et al. 2014) might be significantly related to high temperatures and more affected by socioeconomic differences than cardiovascular mortality.

Another limitation of this study is that the associations observed for data aggregated at district level may not necessarily represent associations existing at an individual level—the so-called ecological fallacy issue (Wakefield and Salway 2001). Similarly, the associations between mortality and explanatory variables observed for the whole group of districts may vary spatially, as demonstrated by the stratified analysis for districts with *low*, *intermediate* and *high SES*. However, as we did not find any significant spatial autocorrelation in the residuals from baseline mortality nor in residuals from the step-wise regression procedure, we did not use any spatially varying coefficient model.

Finally, the study may potentially be subject of the modifiable areal unit problem as all variables were aggregated to district spatial units. Repeating the study at different analysis level may produce variations in the results (Openshaw and Taylor 1981). However, the results for the individual districts and for aggregated regions supported each other.

Another issue of this study is the use of gridded temperature data. As the spatial distribution of the grid is 25 × 25 km, it does not fully represent fine-scale thermal and environmental conditions in individual municipalities. This is particularly true in the *low SES-Urban* districts which are located in areas with large differences in topography and thermal conditions ranging from relatively large cities situated in a warm climatic region to surrounding mountain areas with cooler climate (Tolasz et al. 2007). In order to take this issue into account, temperature data was weighted by population counts in every grid box when mean daily temperature in districts was calculated and percentiles were used instead of absolute temperature thresholds for the definition of hot days. Nevertheless, the effect of average summer temperature and average altitude on mortality deviations on hot days may be partly underestimated in the correlation and regression analyses. On the other hand, the gridded temperature data, representing spatial means rather than point values (Plavcová and Kyselý 2010), allow capturing temperature conditions in individual districts better than raw station data or their averages.

4.5 Conclusions

In this study we analysed spatial patterns of links between high temperature extremes and daily cardiovascular mortality at a district level. We considered differences between districts' demographics, socioeconomic status, as well as physical-environmental conditions.

The largest relative mortality deviations on hot days were generally observed in the warmest regions of the Czech Republic that involved most urbanized areas. We revealed significant effects of physical environment (altitude, mean summer temperature, artificial surface) and urbanization (population density) on excess cardiovascular mortality on hot days when all districts in the Czech Republic were considered together. The level of socioeconomic status played a relevant role only in the most deprived populations.

Analysis of mortality deviation patterns for larger groups of districts during two weeks after a hot spell's onset revealed no mortality displacement in large municipalities, while most of the excess deaths in rural districts may be attributed to harvesting. Highest population count and density, highest average temperature due to low altitude, and generally worst thermal conditions due to high proportion of artificial surface were the factors associated with largest excess cardiovascular mortality due to hot spells. In addition, long-term exposure to highest environmental and socioeconomic deprivation within the Czech Republic in urban districts with low socioeconomic status may have a significant effect on lagged excess mortality associated with hot spells due to the higher percentage of people with chronic cardiovascular disease. Inasmuch as coal mining and associated heavy industry (energetics, metallurgy) are typical economic activities in these districts, their populations are potentially at risk of increasing social deprivation in future due to a decline of mining and industrial transformation. The significant relationship between decreased socioeconomic status and increased heat-related mortality within the most deprived district group highlights the role of socioeconomic status in adaptability to heat across the population.

We identified districts and regions in the Czech Republic whose populations are most at risk of excess mortality due to heat stress and might be at increasing risk in the future. Our results are potentially useful for better targeting biometeorological forecasts and warnings, although larger regions rather than individual districts need to be considered to achieve a reasonable statistical power. Such other health outcomes as emergency calls and hospital admissions for respiratory and heat-related diseases should be considered in follow-up research regarding the effects of heat stress on public health in the Czech Republic.

Acknowledgments The study was supported by the Czech Science Foundation under project P209/11/1985. Thanks are due to Bohumil Kříž and Jan Kynčl, National Institute of

Public Health, for preparing epidemiological data sets as well as for useful discussions concerning their interpretation, and Ladislav Kážmér, Institute of Sociology CAS, for useful discussion concerning the Census database and its interpretation. Special thanks go to the Erasmus+ programme that enabled Aleš Urban a traineeship at Humboldt University in Berlin.

Author Contributions Jan Kyselý defined the initial focus of this study. Aleš Urban together with Katrin Burkart, Jan Kyselý, Christian Schuster, and Tobia Lakes carried out the final research design. Hana Hanzlíková and Aleš Urban were responsible for gathering, cleaning and standardization of the mortality data. Petr Štěpánek gathered the temperature data and prepared the gridded dataset. Aleš Urban was responsible for gathering, clearing and analysis of the socioeconomic and environmental data and their transformation to districts. Aleš Urban, Katrin Burkart and Jan Kyselý contributed to defining the time series analysis approach. Eva Plavcová performed nonparametric tests of mortality deviations. Aleš Urban performed most analyses, prepared initial interpretation of results and drafted the first manuscript. Katrin Burkart, Jan Kyselý, Christian Schuster, and Eva Plavcová provided critical revisions of the manuscript. All authors contributed to the final interpretation of results, and read and approved the final manuscript.

Conflicts of Interest The authors declare no conflict of interest.

4.6 References

Ahmad O, Boschi-Pinto C, Lopez AD, et al. (2001) *Age Standardization of Rates: A New WHO Standard*; World Health Organization: Geneva, Switzerland.

Alcoforado MJ, Andrade H (2006) Nocturnal urban heat island in Lisbon (Portugal): Main features and modelling attempts. *Theor Appl Climatol* 84:, 151–159.

Arnfield AJ (2003) Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int J Climatol* 23: 1–26. doi: 10.1002/joc.859

Baccini M, Kosatsky T, Biggeri A (2013) Impact of summer heat on urban population mortality in Europe during the 1990s: An evaluation of years of life lost adjusted for harvesting. *PLoS ONE*, doi:10.1371/journal.pone.0069638.

Ballester J, Rodó X, Giorgi F (2009) Future changes in Central Europe heat waves expected to mostly follow summer mean warming. *Clim Dyn* 35: 1191–1205. doi: 10.1007/s00382-009-0641-5

Bao J, Li X, Yu C (2015) The construction and validation of the heat vulnerability index, a review. *Int J Environ Res Public Health* 12: 7220–7234.

Basu R (2009) High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environ Health* 8: 40.

Blatecká K (2006) *The basic characteristics of Czech rural areas*. Diploma thesis. Masaryk University Brno (in Czech, with summary in English). http://is.muni.cz/th/137827/esf_m/Diplomova_prace.pdf. Accessed on 14 August 2013.

Błażejczyk K, Epstein Y, Jendritzky G, et al. (2012) Comparison of UTCI to selected thermal indices. *Int J Biometeorol* 56: 515–535.

Bobb JF, Peng RD, Bell ML, et al. (2014) Heat-related mortality and adaptation to heat in the United States. *Environ Health Perspect* 122: 811–816.

Boeckmann M, Rohn I (2014) Is planned adaptation to heat reducing heat-related mortality and illness? A systematic review. *BMC Public Health*. doi:10.1186/1471-2458-14-1112.

Bhaskaran K, Gasparrini A, Hajat, S, et al. (2013) Time series regression studies in environmental epidemiology. *Int J Epidemiol* 42: 1187–1195.

Brook RD, Franklin B, Cascio W, et al. (2004) Air pollution and cardiovascular disease: A statement for healthcare professionals from the expert panel on population and prevention science of the American Heart Association. *Circulation* 109: 2655–2671 doi: 10.1161/01.CIR.0000128587.30041.C8

Bubbico RL, Dijkstra L (2011) *The European regional Human Development and Human Poverty Indices Regional Focus*. Available online: http://ec.europa.eu/regional_policy/sources/docgener/focus/2011_02_hdev_hpov_indices.pdf. Accessed on 20 September 2015.

Buckley JP, Samet JM, Richardson DB (2014) Commentary: Does air pollution confound studies of temperature? *Epidemiology*, 25: 242–245.

Burkart K, Khan MMH, Schneider A, et al. (2014) The effects of season and meteorology on human mortality in tropical climates: a systematic review. *Trans R Soc Trop Med Hyg* 108: 393–401. doi: 10.1093/trstmh/tru055

Burkart K, Meier F, Schneider A, et al. (2015) Modification of heat-related mortality in an elderly urban population by vegetation (Urban Green) and proximity to water (Urban Blue): Evidence from Lisbon, Portugal. *Environ Health Perspect*, doi:10.1289/ehp.1409529.

Chen H, Goldberg MS (2009) The effects of outdoor air pollution on chronic illnesses. *McGill J Med* 12: 58–64.

Cheng X, Su H (2010) Effects of climatic temperature stress on cardiovascular diseases. *Eur J Intern Med* 21: 164–167. doi: 10.1016/j.ejim.2010.03.001

CHMI (2015) Czech Hydrometeorological Institute. Air Pollution in the Czech Republic. Available online: http://portal.chmi.cz/files/portal/docs/uoco/isko/tab_roc/tab_roc_EN.html. Accessed on 20 October 2015.

CZSO (2004) Czech Statistical Office—Nomenclature of Territorial Units for Statistics (CZ-NUTS)—2004. (in Czech Language) Available online: https://www.czso.cz/csu/czso/klasifikace_uzemnich_statistickych_jednotek_-cz_nuts-. Accessed on 20 October 2015.

Davídkovová H, Kyselý J, Kříž B, et al. (2013) Trends in cardiovascular mortality and hospitalisations, and potential contribution of in hospital case-fatality rates to changes in national mortality in the Czech Republic 1994–2009. *Heart* 99: 409–416.

Davídkovová H, Plavcová E, Kynčl J, et al. (2014) Impacts of hot and cold spells differ for acute and chronic ischaemic heart diseases. *BMC Public Health* 14: 480.

Dugord PA, Lauf S, Schuster C, et al. (2014) Land use patterns, temperature distribution, and potential heat stress risk—The case study Berlin, Germany. *Comput Environ Urban Syst* 48: 86–98.

Dütemeyer D, Barlag AB, Kuttler W, et al. (2013) Measures against heat stress in the city of Gelsenkirchen, Germany. *DIE ERDE* 144: 181–201.

Dzúrová D (1993) *Zdravotní stav obyvatel a kvalita životního prostředí: regionální souvislosti.* Ph.D. Thesis. Faculty of Science, Charles University, Prague, Czech Republic; p. 136 (in Czech).

EUROSTAT (2015) Local Administrative Units. Available online: http://ec.europa.eu/eurostat/web/nuts/local-administrative-units. Accessed on 20 October 2015.

Fischer EM, Oleson KW, Lawrence DM (2012) Contrasting urban and rural heat stress responses to climate change. *Geoph Res Lett* 39: L03705. doi: 10.1029/2011GL050576

Gabriel KMA, Endlicher WR (2011) Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. *Environ Pollut* 159: 2044–2050. doi:10.1016/j.envpol.2011.01.016.

Getis A, Ord JK (1992) The analysis of spatial association by use of distance statistics. *Geogr Anal* 24: 189–206.

Gosling SN, Lowe JA, McGregor GR, et al. (2009a) Associations between elevated atmospheric temperature and human mortality: a critical review of literature. *Clim Change* 92(3–4): 299–341. doi: 10.1007/s10584-008-9441-x.

Gosling SN, McGregor GR, Lowe Ja (2009b) Climate change and heat-related mortality in six cities Part 2: climate model evaluation and projected impacts from changes in the mean and variability of temperature with climate change. *Int J Biometeorol* 53: 31–51. doi: 10.1007/s00484-008-0189-9

Gosling SN, McGregor GR, Lowe JA (2012) The benefits of quantifying climate model uncertainty in climate change impacts assessment: An example with heat-related mortality change estimates. *Clim Chang* 112: 217–231.

Gosling SN, McGregor GR, Páldy A (2007) Climate change and heat-related mortality in six cities part 1: model construction and validation. *Int J Biometeorol* 51: 525–40. doi: 10.1007/s00484-007-0092-9

GPW (2005) Gridded Population of the World, Version 3, Data Collection. Center for International Earth Science Information Network (CIESIN), Colombia Univesity. Available online: http://sedac.ciesin. columbia.edu/data/collection/gpw-v3. Accessed on 20 September 2015.

Hajat S, Kosatky T (2010) Heat-related mortality: a review and exploration of heterogeneity. *J Epidemiol Community Health* 64: 753–60. doi: 10.1136/jech.2009.087999

Hajat S, Kovats RS, Lachowycz K (2007) Heat-related and cold-related deaths in England and Wales: who is at risk? *Occup Environ Med* 64: 93–100. doi: 10.1136/oem.2006.029017

Hanzlíková H, Plavcová E, Kynčl J, et al. (2015) Contrasting patterns of hot spell effects on morbidity and mortality for cardiovascular diseases in the Czech Republic, 1994-2009. *Int J Biometeorol*. doi: 10.1007/s00484-015-0974-1

Harlan SL, Declet-barreto JH, Stefanov WL, et al. (2013) Neighborhood effects on heat deaths : social and environmental predictors of vulnerability in Maricopa county, Arizona. *Environ Health Perspect* 121: 197–204.

Harrell FE (2004) Hmisc S. Function Library.. Available online: http://biostat.mc.vanderbilt.edu/s/Hmisc. Accessed on 8 October 2015.

Hattis D, Ogneva-Himmelberger Y, Ratick S (2012) The spatial variability of heat-related mortality in Massachusetts. *Appl Geogr* 33: 45–52. doi: 10.1016/j.apgeog.2011.07.008

Henderson G (2005) Home air conditioning in Europe – how much energy would we use if we became more like American households? In: Attali S, Tillerson K (eds.). Energy Savings: What Works & Who Delivers? *ECEEE* 2005 Summer Study. pp 541–550.

Hondula DM, Barnett AG (2014) Heat-related morbidity in Brisbane, Australia: Spatial variation and area-level predictors. *Environ Health Perspect* 122: 831–836.

Hondula DM, Davis RE, Leisten MJ, et al. (2012) Fine-scale spatial variability of heat-related mortality in Philadelphia County, USA, from 1983-2008: a case-series analysis. *Environ Health* 11: 16. doi: 10.1186/1476-069X-11-16

Huang C, Barnett, AG, Wang X, et al. (2011) Projecting future heat-related mortality under climate change scenarios: A systematic review. *Environ Health Perspect* 119: 1681–1690.

Huynen MMTE, Martens P, Schram D, et al. (2001) The impact of heat waves and cold spells on mortality rates in the Dutch population. *Environ Health Perspect* 109: 463–470. doi: 10.2307/3454704

IPCC (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Johnson DP, Stanforth A, Lulla V, et al. (2012) Developing an applied extreme heat vulnerability index utilizing socioeconomic and environmental data. *Appl Geogr* 35: 23–31. doi: 10.1016/j.apgeog.2012.04.006

Kaufman JD (2012) Does air pollution accelerate progression of atherosclerosis? *J Am Coll Cardiol* 56: 1809–1811. doi: 10.1016/j.jacc.2010.05.054

Kenney WL, Munce TA (2003) Invited review: aging and human temperature regulation. *J Appl Physiol* 95(6): 2598–603.

Klein Rosenthal J, Kinney PL, Metzger KB (2014) Intra-urban vulnerability to heat-related mortality in New York City, 1997–2006. *Health Place* 30: 45–60.

Kovach MM, Konrad CE, II, Fuhrmann CM (2015) Area-level risk factors for heat-related illness in rural and urban locations across North Carolina, USA. *Appl Geogr* 60: 175–183.

Kyselý J (2004) Mortality and displaced mortality during heat waves in the Czech Republic. *Int J Biometeorol* 49(2): 91–97.

Kyselý J, Huth R (2004) Heat-related mortality in the Czech Republic examined through synoptic and "traditional" approaches. *Clim Res* 25: 265–274. doi: 10.3354/cr025265

Kyselý J, Kříž B (2008) Decreased impacts of the 2003 heat waves on mortality in the Czech Republic: an improved response? *Int J Biometeorol* 52: 733–745. doi: 10.1007/s00484-008-0166-3

Kyselý J, Plavcová E (2010) A critical remark on the applicability of E-OBS European gridded temperature dataset for validating control climate simulations. *J Geoph Res* 115: D23118. doi: 10.1029/2010JD014123

Kyselý J, Plavcová E (2012) Declining impacts of hot spells on mortality in the Czech Republic, 1986–2009: adaptation to climate change? *Clim Change* 113: 437–453. doi: 10.1007/s10584-011-0358-4

Kyselý J, Plavcová E, Davídkovová H, et al. (2011) Comparison of hot and cold spell effects on cardiovascular mortality in individual population groups in the Czech Republic. *Clim Res* 49: 113–129. doi: 10.3354/cr01014

Laschewski G, Jendritzky G (2002) Effects of the thermal environment on human health: an investigation of 30 years of daily mortality data from SW Germany. *Clim Res* 21: 91–103. doi: 10.3354/cr021091

Maier G, Grundstein A, Jang W, et al. (2014) Assessing the performance of a vulnerability index during oppressive heat across Georgia, United States. *Weather Clim Soc* 6: 253–263.

Matzarakis A, Muthers S, Koch E (2010) Human biometeorological evaluation of heat-related mortality in Vienna. *Theor Appl Climatol* 105: 1–10.

Medina-Ramón M, Schwartz J (2007) Temperature, temperature extremes, and mortality: a study of acclimatization and effect modification in 50 United States cities. *Occup Environ Med* 64: 827–833. doi: 10.1136/oem.2007.033175

Mercer JB (2002) Cold – an underrated risk factor for health. *Environ Res Environ Res* 92: 8–13. doi: 10.1016/S0013-9351(02)00009-9

McMichael AJ, Woodruff RE, Hales S (2006) Climate change and human health: present and future risks. *Lancet* 367(9513): 859–869.

Novák M (2013) Use of the UTCI in the Czech Republic. *Geogr Pol* 86: 21–28.

OECD (2015) Income Distribution Database (IDD): Gini, Poverty, Income, Methods and Concepts. Available online: http://www.oecd.org/social/income-distribution-database.htm. Accessed on 20 September 2015.

Openshaw S, Taylor PJ (1981) The modifiable areal unit problem. In Wrigley N, Bennett RJ (Eds.) *Quantitative Geography: A British View*; Routledge: Boston, MA, USA; pp. 60–69.

Plavcová E, Kyselý J (2010) Relationships between sudden weather changes in summer and mortality in the Czech Republic, 1986–2005. *Int J Biometeorol* 2010, 54: 539–551.

Reid C.E, O'Neill MS, Gronlund CJ, et al. (2009) Mapping community determinants of heat vulnerability. *Environ Health Perspect* 117: 1730–1736.

Reid CE, Mann JK, Alfasso R, et al. (2012) Evaluation of a heat vulnerability index on abnormally hot days: an environmental public health tracking study. *Environ Health Perspect* 120: 715–20. doi: 10.1289/ehp.1103766

Saha MV, Davis, RE, Hondula DM (2014) Mortality displacement as a function of heat event strength in 7 US cities. *Am J Epidemiol* 179: 467–474.

Scherber K, Langner M, Endlicher W (2014) Spatial analysis of hospital admissions for respiratory diseases during summer months in Berlin taking bioclimatic and socio-economic aspects into account. *Geogr Soc Berl* 144: 217–237.

Sheridan SC, Dolney TJ (2003) Heat, mortality, and level of urbanization: measuring vulnerability across Ohio, USA. *Clim Res* 24: 255–265

Šplíchalová A, Šlachtová H, Tomášková H, et al. (2007) Analysis of mortality in the Czech Republic using the newly constructed socio-economic deprivation index. *Epidemiology*, doi:10.1097/01.ede.0000276469.05896.8d.

Tan J, Zheng Y, Tang X, et al. (2010) The urban heat island and its impact on heat waves and human health in Shanghai. *Int J Biometeorol* 54: 75–84 doi: 10.1007/s00484-009-0256-x

Spiezia V (2003) Measuring regional economies. Statistics Brief OECD, No. 6, October 2003. http://www.oecd.org/dataoecd/2/15/15918996.pdf. Accessed on 14 August 2013.

Tolasz R, Míková T, Valeriánová A, et al. (2007) *Climate Atlas of Czechia*; Czech Hydrometeorological Institute: Prague, Czech Republic; p. 254.

Toloo GS, Fitzgerald G, Aitken P, et al. (2013) Are heat warning systems effective? *Environ Health* 12: 27.

Uejio CK, Wilhelmi OV, Golden JS, et al. (2011) Intra-urban societal vulnerability to extreme heat: The role of heat exposure and the built environment, socioeconomics, and neighborhood stability. *Health Place* 17: 498–507.

Unger J (2004) Intra-urban relationship between surface geometry and urban heat island: Review and new approach. *Clim Res* 27: 253–264.

Urban A, Davídkovová H, Kyselý J (2014) Heat- and cold-stress effects on cardiovascular mortality and morbidity among urban and rural populations in the Czech Republic. *Int J Biometeorol* 58: 1057–1068.

Urban A, Kyselý J (2014) Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic. *Int J Environ Res Public Health* 11: 952–67.

Urban A, Kyselý J (2015) Application of spatial synoptic classification in evaluating links between heat stress and cardiovascular mortality and morbidity in Prague, Czech Republic. *Int J Biometeorol.* doi:10.1007/s00484-015-1055-1.

Venables WN, Ripley BD (2002) *Modern Applied Statistics with S*, 4th ed, Springer: New York, NY, USA,.

Vescovi L, Rebetez M, Rong F (2005) Assessing *Public Health* risk due to extremely high temperature events: climate and social parameters. *Clim Res* 30: 71–78. doi: 10.3354/cr030071

Wakefield J, Salway R (2001) A statistical framework for ecological and statistical studies. *J R Stat Soc* 164: 119–137.

Wichmann J, Andersen ZJ, Ketzel M, et al. (2011) Apparent temperature and cause-specific mortality in Copenhagen, Denmark: a case-crossover analysis. *Int J Environ Res Public Health* 8: 3712–27.

Wolf T, McGregor G, Analitis A (2014) Performance assessment of a heat wave vulnerability index for greater London, United Kingdom. *Weather Clim Soc* 6: 32–46.

Wood S (2006) *Generalized Additive Models: An Introduction with R*; Chapman & Hall/CRC: London, UK.

Xu Y, Dadvand P, Barrera-Gomez J, et al. (2013) Differences on the effect of heat waves on mortality by sociodemographic and urban landscape characteristics. *J Epidemiol Community Health* 67: 519–525.

Zacharias S, Koppe C, Mücke H-G (2014) Influence of heat waves on ischemic heart diseases in Germany. *Climate* 2: 133–152.

Zaninović K, Matzarakis A (2014) Impact of heat waves on mortality in Croatia. *Int J Biometeorol* 58: 1135–1145.

5 Application of spatial synoptic classification in evaluating links between heat stress and cardiovascular mortality and morbidity in Prague, Czech Republic

Aleš Urban [1,2], Jan Kyselý [1,3]

[1] *Institute of Atmospheric Physics AS CR, Boční II 1401, 141 31 Prague 4, Czech Republic*

[2] *Faculty of Science, Charles University, Albertov 6, 128 43 Prague 2, Czech Republic*

[3] *Faculty of Environmental Sciences, Czech University of Life Sciences, Prague, Czech Republic*

Abstract Spatial synoptic classification (SSC) is here first employed in assessing heat-related mortality and morbidity in central Europe. It is applied for examining links between weather patterns and cardiovascular (CVD) mortality and morbidity in an extended summer season (16 May–15 September) during 1994–2009. As in previous studies, two SSC air masses (AMs) – dry tropical (DT) and moist tropical (MT) – are associated with significant excess CVD mortality in Prague, while effects on CVD hospital admissions are small and insignificant. Excess mortality for ischaemic heart diseases is more strongly associated with DT, while MT has adverse effect especially on cerebrovascular mortality. Links between the oppressive AMs and excess mortality relate also to conditions on previous days, as DT and MT occur in typical sequences. The highest CVD mortality deviations are found one day after a hot spell's onset, when temperature as well as frequency of the oppressive AMs are highest. Following this peak is typically DT- to MT-like weather transition, characterized by decrease in temperature and increase in humidity. The transition between upward (DT) and downward (MT) phases is associated with the largest excess CVD mortality, and the change contributes to the increased and more lagged effects on cerebrovascular mortality. The study highlights the importance of critically evaluating SSC's applicability and benefits within warning systems relative to other synoptic and epidemiological approaches. Only a subset of days with the oppressive AMs is associated with excess mortality, and regression models accounting for possible meteorological and other factors explain little of the mortality variance.

Keywords: Spatial synoptic classification, mortality, morbidity, cardiovascular diseases, central Europe

5.1 Introduction

In the past two decades, extreme heat waves have been documented as the deadliest of atmospheric hazards in mid-latitudes (Kirch et al. 2005; Kosatsky 2005; EEA 2010; Barriopedro et al. 2011). Due to a projected rise in global mean temperature in the 21st century, the frequency of events similar to the heat waves in 2003 (Larsen 2006) and 2010 (Barriopedro et al. 2011) is expected to increase (Ballester et al. 2009; IPCC 2014). Consequently, increased heat-related mortality and decreased cold-related mortality are projected if adaptation to warmer climate is insufficient (Gosling et al. 2009; Muthers et al. 2010). Uncertainty concerning the climate change impact on heat-related mortality is nevertheless great, as physiological, behavioural and technological adaptation may considerably modify climate–mortality relationships (Christidis et al. 2010; Matzarakis et al. 2010; Kyselý and Plavcová 2012; Ebi et al. 2014).

Many epidemiological studies employ traditional approaches to heat-related mortality and morbidity assessment and associate health outcomes with air temperature or another simple measure of equivalent temperature considering synergistic effects of air temperature, humidity and/or wind speed (heat index, apparent temperature, etc.; Basu 2009; Ye et al. 2012). These indices do not, however, represent the actual biometeorological conditions (Jendritzky et al. 2012). Indices based upon human heat budget, such as PET (Höppe 1999; Matzarakis et al. 1999) and UTCI (Jendritzky et al. 2012), on the other hand, consider atmospheric conditions as well as complex metabolic processes in the human body (Jendritzky et al. 2012). These, however, require specific input data (Weihs et al. 2012) which may not be available for application in bioclimatic and epidemiological studies (Urban and Kyselý 2014).

The limitations associated with a lack of appropriate input data can to some extent be avoided by a synoptic climatological approach. Such methodology takes into account the entire suite of daily weather elements (air temperature, a humidity variable, total cloud amount, wind components, and atmospheric pressure) that are classified into air masses (weather types) with meteorologically homogeneous conditions (Davis and Kalkstein 1990). Two basic types of synoptic classifications which are employed in human biometeorology in order to determine air masses with adverse effect on human mortality are termed the 'temporal synoptic index' (TSI; Kalkstein and Corrigan 1986) and 'spatial synoptic classification' (SSC; Kalkstein et al. 1996; redeveloped by Sheridan 2002). While TSI is a 'fully-automated' classification approach using principal component analysis (PCA) and cluster analysis (CA) in order to define oppressive air masses, the 'hybrid' SSC classifies each day into one of six weather types manually predetermined by so-called 'sliding seed days' typical for the local climatology (Sheridan 2002).

Both TSI and SSC approaches have been employed in investigating heat-related mortality and morbidity across wide geographical ranges (Kyselý et al. 2010; Hondula et al. 2014). Heat-and-health-warning systems based either on TSI (Kalkstein et al. 1996) or SSC (Sheridan and Kalkstein 2004) have been developed in numerous cities, particularly in the US (Hondula et al. 2014), and their benefits in saving both human lives and costs have been documented (Ebi et al. 2004; Toloo et al. 2013). Despite the availability of an SSC calendar in Europe (Bower et al. 2007), there exist gaps in both research and application of SSC, especially in central Europe (Hondula et al. 2014). Although the TSI weather-type classifications already have been used for heat-related mortality assessment in the Czech Republic (Kyselý and Huth 2004) with results comparable to those from the traditional approach (Kyselý 2004), no further research into this topic has been conducted.

Although heat-related mortality has been documented also among rural populations (Sheridan and Dolney 2003; Gabriel and Endlicher 2011; Urban et al. 2014), urban populations in particular are strongly affected by significantly increased mortality during heat waves (Loughnan et al. 2008; O'Neill et al. 2009; Gabriel and Endlicher 2011). In addition to the physically altered environment of the urban heat island (Arnfield 2003), higher percentages of elderly, social deprived (homeless, unemployed) and/or isolated populations (people living alone, immigrants, ethnic minorities) are factors increasing heat-related morbidity (Knowlton et al. 2009; Ye et al. 2012) and mortality (Semenza et al. 1996; Hattis et al. 2012; Loughnan et al. 2013) in cities. The population groups most affected by heat stress are young children and the elderly (Kovats et al. 2004; Basu 2009; Knowlton et al. 2009), especially women (Hajat et al. 2007; Matzarakis et al. 2010; Kyselý et al. 2011). Persons in poor physical and medical condition (Kenney and Munce 2003), and particularly those with chronic cardiovascular or respiratory disorders, are at highest risk (McMichael 2006; Cheng and Su 2010; Davídkovová et al. 2014).

In this study, the SSC approach is employed for the first time for heat-related mortality assessment in central Europe, in order to (i) identify oppressive air masses associated with increased cardiovascular (CVD) mortality and morbidity in Prague, Czech Republic; (ii) examine meteorological as well as non-meteorological (persistence, time in sequence) characteristics of the oppressive air masses and their effects on CVD mortality and morbidity; and (iii) examine possible association between oppressive air masses and hot spells with respect to their meteorological characteristics and mortality impacts.

5.2 Data and methods

5.2.1 Epidemiological data

Daily mortality (number of deaths) and morbidity (number of hospital admissions) for cardiovascular disease (CVD – codes I00–I99 according to the International Statistical Classification of Diseases, 10th Revision [ICD–10]) in Prague, Czech Republic (ca 1.2 million inhabitants during the examined years) were obtained for the period 1994–2009 from the Institute of Health Information and Statistics and the Czech Statistical Office. The data include the primary cause of each death or hospital admission.

To account for long-term changes in mortality and morbidity (related to demographics, health care and lifestyle changes) as well as short-term variations due to annual and weekly cycles, the daily numbers of deaths/hospital admissions were standardized. We employed an indirect standardization procedure analogous to one used previously (e.g. Whitman et al. 1997; Smoyer et al. 2000; Kyselý 2004), through which a series of daily excess mortality/morbidity was established by calculating deviations of the observed and expected (baseline) mortality/morbidity for each day of the examined period.

The expected number of deaths/hospital admissions $M_0(y,d)$ for year y (y = 1994, ... 2009) and day d (d = 1, ... 365) was determined according to the formula (Kyselý 2004)

$$M_0(y,d) = M_0(d).W(y,d).Y(y) .$$

In the equation, $M_0(d)$ denotes the mean daily mortality/morbidity on day d in a year (computed from the mean annual cycle over 1994–2009 smoothed by 15-day running means for mortality data; morbidity data were not smoothed, in order to avoid "spreading" the effects of public holidays, on which the number of admissions is substantially lower, to surrounding calendar days); $W(y,d)$ is a correction factor for the observed weekly cycle of mortality/morbidity, calculated separately for individual days of the week and defined as the ratio of the mean mortality/morbidity on a given day to the overall mean mortality/morbidity; and $Y(y)$ is a correction factor for the observed year-to-year changes in mortality/morbidity, defined as the ratio of the number of deaths/hospital admissions in year y to the mean annual number of deaths/hospital admissions during the analysed period. In calculating $W(y,d)$, all public holidays were excluded.

Mortality from CVDs comprises more than 50% of total mortality in the Czech Republic. Among CVDs, ischaemic heart disease (IHD) and cerebrovascular disease (CD) constitute the two main groups, together responsible for more than 60% of all CVD deaths in Prague (Urban et al. 2014). The percentage of death certificates based on autopsy is relatively high in the Czech Republic and comparable with that in western European countries (Davídkovová et al. 2013).

5.2.2 Spatial synoptic classification (SSC)

The SSC developed for Prague by Bower et al. (2007) according to Sheridan (2002) is employed. The daily calendar of air masses (weather types) is available online at the SSC homepage (http://sheridan.geog.kent.edu/ssc.html). We examined associations between CVD mortality and morbidity deviations and SSC air masses (AMs) in the warm season (16 May–15 September) during 1994–2009. The classification recognizes six basic AMs: dry polar (DP), dry moderate (DM), dry tropical (DT), moist polar (MP), moist moderate (MM), and moist tropical (MT) supplemented with a transition type (T). Additional MT subtypes (MT+ and MT++) were included into the MT category, as the occurrence of these subtypes is rather low in Europe (see the SSC homepage and results below). 20 days were removed from the analysis because air masses were not specified in the calendar.

5.2.3 Meteorological data

Data on air temperature (T, in °C), dew-point temperature (Td, °C), wind speed at 10 m above the surface (WS, $m \cdot s^{-1}$), relative humidity (RH, %), total cloud amount (TCA, tenths) and atmospheric pressure (SLP, hPa) from the Prague-Ruzyně (airport) station were available for the same period of 1994–2009 from the Czech Hydrometeorological Institute. The data had been measured three times daily in standard climatic terms (7:00, 14:00 and 21:00 local time).

Air pollution data on the 8-hour daily maximum of tropospheric ozone (O_3) and daily average concentrations of PM_{10} (both in $\mu g/m^3$) in the city of Prague during 1994–2009 were also provided by the Czech Hydrometeorological Institute.

5.2.4 Oppressive air masses

Oppressive air masses (OAMs) are defined as those AMs associated with average excess mortality/morbidity significantly different from zero according to the one-sample *t*-test with a two-sided alternative hypothesis (p-value < 0.05). To evaluate the contribution of AMs to days with heightened mortality/morbidity, an occurrence ratio was calculated as the frequency of each AM type among the 50 days with the highest excess mortality/morbidity relative to its mean frequency in the analysed period (cf. Kyselý and Huth 2004). Significance of the ratios higher than 1 was tested by one-tail *z*-test for difference of two proportions (similarly to Lee 2015). As there have been documented lagged effects of heat on mortality/morbidity (e.g. Huynen et al. 2001; Kyselý and Huth 2004; Schwartz et al. 2004), we analyzed average excess mortality/morbidity and its relationship to AMs on days D−3 to D+4 around OAMs occurrence.

In order to quantify relationships between health and weather conditions within OAMs, stepwise regression analysis on days classified as having OAMs was performed. All independent variables in the step-wise regression models are shown in Table 5.1. They included weather elements that may affect heat-related mortality (air temperature [T] and dew-point temperature [Td] measured three times a day; dew-point depression as the difference T−Td; daily average of T, Td, total cloud amount [TCA], and wind speed [WS]), air pollution [O_3 and PM_{10}], as well as non-meteorological factors to account for long-term adaptation effects (year), adaptation effects through the warm season (number of oppressive days since the beginning of the season and time of season) and duration of the OAM conditions (day in sequence).

Bidirectional stepwise regression procedure was conducted, using the 'MASS' package in R (version 2.15.2). The 'stepAIC' function adds or drops variables from or to the model repeatedly, fits those models and computes a table of the changes in fit according to the Akaike information criterion (AIC) (see Venables and Ripley 2002). Final model components were chosen by AIC and amount of variance explained, i.e. the model with the lowest AIC and all significant parameters (according to F-test, p<0.05) was selected.

Table 5.1 Independent variables in stepwise regression models for relative daily excess mortality within the oppressive AMs.

Meteorological variables	
*T*07, *T*14,*T*21	air temperature at 7:00, 14:00, and 21:00 local time
Td7, Td14, Td21	dew-point temperature at 7:00, 14:00, and 21:00 local time
T, Td, WS, TCA	average daily temperature, dew-point temperature, wind speed, total cloud amount
*X*_1	variable *X* lagged by 1 day
dT	dew-point depression (T−Td)
Air pollution variables	
O_3	8-hour daily maximum concentration of tropospheric ozone
PM_{10}	daily average concentration of PM_{10}
Non-meteorological variables	
TOS	time of season (16 May = 1; 15 September = 123)
YEAR	year
DIS	day in sequence of OAMs (DT and MT together)
OAMy	number of days with the oppressive air mass (DT or MT) since the beginning of the season

5.3 Results

5.3.1 Air mass characteristics

Table 5.2 shows climatology of individual AMs in the warm season (16 May–15 September) during 1994–2009 in Prague. Moist moderate (MM) and dry moderate (DM), with average air temperature 16.2 and 17.8 °C, respectively, were the AMs occurring most frequently. In general, the moist air masses are more common than are the dry ones. DT is the AM with the highest mean daily temperature (22.9 °C) but smallest relative humidity, wind speed and cloud cover. MT is a colder (20.7 °C) but more humid weather type with larger cloud cover than has DT. Both DT and MT are associated with the highest mean concentrations of air pollutants (O_3 and PM_{10}) among the AMs, and these exceed air quality standards in the Czech Republic (Act No. 201/2012 Coll.). Statistics for the MT category involve also the MT+ subtype, with mean relative humidity (66.7%) similar to MT while mean daily temperature is comparable to DT (22.6 °C). Because MT+ occurred only on 31 days during the 16-year period (about 2 days per year), this subtype is not examined separately but was included into the MT category for further analysis.

Table 5.2 Climatological characteristics of individual AMs in Prague during warm season (16 May–15 September), 1994–2009. O_3 values represent 8-hour daily maximum concentrations; values for other variables indicate daily means.

SSC	Relative frequency (%)	*T* (°C)	Td (°C)	RH (%)	WS ($m \cdot s^{-1}$)	TCA (tenths)	O_3 ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)
DP	5.7	12.3	6.2	65	3.7	6.1	100	26
DM	22.0	17.8	10.1	62	2.9	4.3	91	27
DT	**7.7**	**22.9**	**12.1**	**52**	**2.8**	**3.5**	**123**	**35**
MP	10.2	11.7	8.7	82	4.5	8.5	86	24
MM	32.0	16.2	12.2	78	3.8	7.7	112	32
MT	**14.2**	**20.7**	**14.7**	**68**	**2.9**	**5.7**	**143**	**41**
T	8.2	16.8	11.0	71	4.3	6.7	69	19

5.3.2 Mortality and morbidity associated with air masses

Figure 1 shows box plots representing distribution of relative CVD mortality (left) and morbidity (right) anomalies within individual AMs. Tropical air masses – DT and MT – are the only two AMs associated with a significant (*t*-test at $p<0.05$) increase of mortality due to CVD. In the following text, it is those two AMs which are regarded as oppressive (OAMs). Mean excess mortality from all CVD is slightly higher for DT (9.8%) than for MT (7.2%), and the deviation is highly significant ($p<0.001$) in both cases (Table 3). By contrast, the polar air masses (DP and MP) are those associated with the lowest mean mortality anomalies (−6.7% and −2.8%, respectively). Although we did not consider MT+ in this study due to its low frequency, this AM – if evaluated separately – is linked to the highest mean CVD mortality deviation in Prague (16.7%, $p<0.01$).

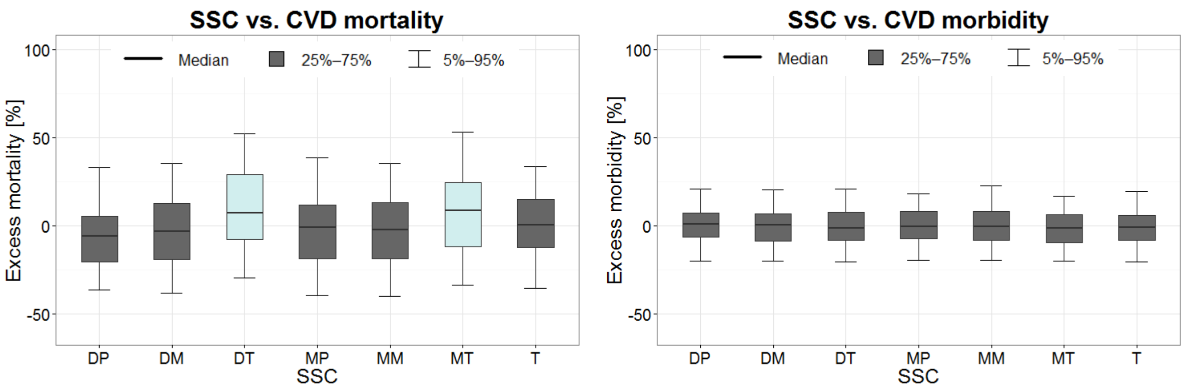

Figure 5.1 Box plots of relative excess CVD mortality and morbidity for individual AMs in Prague, 16 May–15 September, 1994–2009. The oppressive AMs are marked by *light bars*.

Table 5.3 Mean relative excess mortality (*left*) and morbidity (*right*) due to all cardiovascular disease (CVD), ischaemic heart disease (IHD), and cerebrovascular disease (CD) for individual AMs. *Ratio* = occurrence ratio calculated as the relative frequency of each air mass type among the 50 days with the highest excess mortality against its mean (climatological) frequency.

	Mortality						**Morbidity**					
SSC	**Excess CVD mortality (%)**	**Ratio**	**Excess IHD mortality (%)**	**Ratio**	**Excess CD mortality (%)**	**Ratio**	**Excess CVD morbidity (%)**	**Ratio**	**Excess IHD morbidity (%)**	**Ratio**	**Excess CD morbidity (%)**	**Ratio**
DP	-6.7*	0.35	-2.9	1.04	-9.5*	0.35	1.1	0.70	-0.0	0.00	1.6	1.04
DM	-2.6*	0.82	-4.6*	0.82	-2.0	0.91	-0.1	1.09	-0.2	1.18	1.9	1.27
DT	**9.8***	**2.60†**	**7.4***	**1.82†**	**7.1**	**0.78**	**-0.6**	**0.78**	**-1.9**	**1.04**	**1.4**	**1.56**
MP	-2.6	0.79	1.8	1.18	-8.5*	0.20	-0.1	0.39	-0.5	0.39	-4.1*	0.39
MM	-2.5*	0.44	-1.6	0.94	-2.2	1.06	0.2	1.31	0.7	1.31	-0.7	0.94
MT	**7.2***	**2.27†**	**2.5**	**0.99**	**13.3***	**2.13†**	**-1.5***	**0.71**	**-1.2**	**0.71**	**-0.7**	**1.13**
T	-0.3	0.48	4.2	0.73	0.1	0.73	-0.4	1.21	-0.9	1.21	-0.6	0.48

* denotes statistically significant excess mortality values according to two-sided *t*-test ($p<0.05$)

† denotes statistically significant ratio values according to *z*-test for difference of two proportions ($p<0.05$)

The mortality deviations tend to increase from the polar air masses to the tropical ones for the overall group of CVDs and the CD subgroup, while the pattern is much less clear for the IHD mortality (Table 5.3). One may also notice differences between the effects of DT and MT on the two CVD subgroups. While DT is associated with significant increase of mortality due to IHD (7.4%), MT has significant impact on mortality due to CD (13.3%). The effect of MT is significantly higher on mortality from CD than from IHD (2.5%) according to the two-sample *t*-test ($p<0.01$). The ratio values support significance of these patterns: while DT occurs 1.8 times more often on 50 days with the highest IHD mortality, MT, on the other hand, occurs 2.1 times more often on 50 days with the highest CD mortality in comparison to their mean frequencies. Both ratios are significant according to the test for different proportions ($p<0.05$).

The generally smaller spread between the 5% and 95% quantiles (Figure 5.1) for morbidity versus mortality data is related to the much larger number of hospital admission cases in comparison with the number of deaths. In contrast to mortality, no AM is associated with significantly positive CVD morbidity deviations on the day of occurrence. However, despite the relatively small differences among AMs, we can observe contrasting patterns between mortality and morbidity deviations for individual AMs (Table 5.3). Those AMs associated with large positive mortality deviations are also associated with negative morbidity deviations, and vice versa (cf. DT vs. DP). Moreover, when considering sequences of days D−3 to D+4 around the AMs occurrence, we did not observe any heat-related CVD morbidity neither on days after the DT or MT occurrence. However, we found significant "cold-related" morbidity on days D+2 (2.4%) and D+3 (2.2%) after the moist polar (MP) air mass occurrence. As the MP is the coldest AM, the excess morbidity may be related to relatively cold weather conditions in summer; a similar increase is not found in the mortality data.

5.3.3 Sequences of the oppressive AMs

Figure 5.2 shows mean CVD mortality deviations on days D−3 to D+4 around DT or MT occurrence. While the highest mean mortality deviation occurs one day after DT (10.6%), in the sequence of days around MT, D−1 is the mortality peak day (8.7%). These findings suggest that the effects on mortality may be modified by meteorological conditions (i.e. air mass occurrence) on previous/following days. Specifically in Prague, DT is followed in 46% of cases by another DT and in 33% by MT (so only 21% of days following DT are non-oppressive), while MT is followed in 39% of cases by another MT, only in 6% of cases by DT, and in 55% of cases by non-oppressive AMs, mostly MM (Figure 5.3).

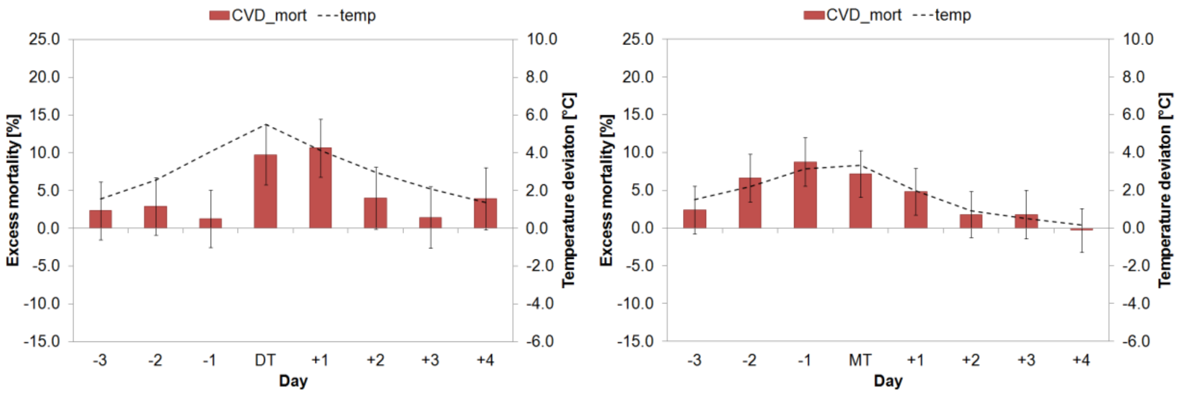

Figure 5.2 Mean relative excess mortality for CVD on days D−3 to D+4 around DT or MT spell occurrence. *Temp* indicates average temperature deviation from the seasonal mean. *Error bars* denote the 95% confidence intervals for the normal distribution.

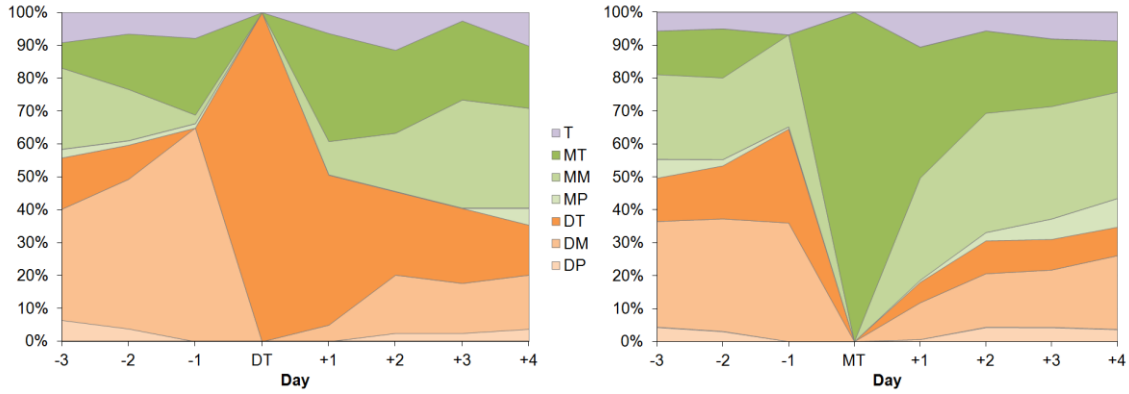

Figure 5.3 Relative frequencies of AMs around DT or MT occurrence (on day 0) in Prague, 16 May–15 September, 1994–2009.

Whereas the average length of DT and MT spells is 2.0 and 1.7 days, respectively, the average length of a spell consisting of DT and MT considered together is 2.4 days. In order to investigate links between the OAMs and hot conditions more comprehensively, we performed additional analysis of the relative frequency of AMs on days D−3 to D+15 during hot spells (at least two consecutive days with average daily temperature above the 95th percentile of its distribution in the examined period of year). Figure 5.4 (left) shows that DT is the most frequent AM on the first 2 days (60% and 67%, respectively), while MT is the most frequent AM in a later phase of hot spells (43% on D+2 to 30% on D+5). When DT and MT are considered together, D+1 is linked with the highest occurrence of the OAMs (90%) within a hot spell. Moreover, this day is characterized by the largest temperature anomaly (7.8 °C) and the largest day-to-day negative pressure change (Figure 5.4, right). This peak is followed by a decline in temperature but an increase in air humidity, corresponding with the increased MT occurrence on days D+2 to D+5.

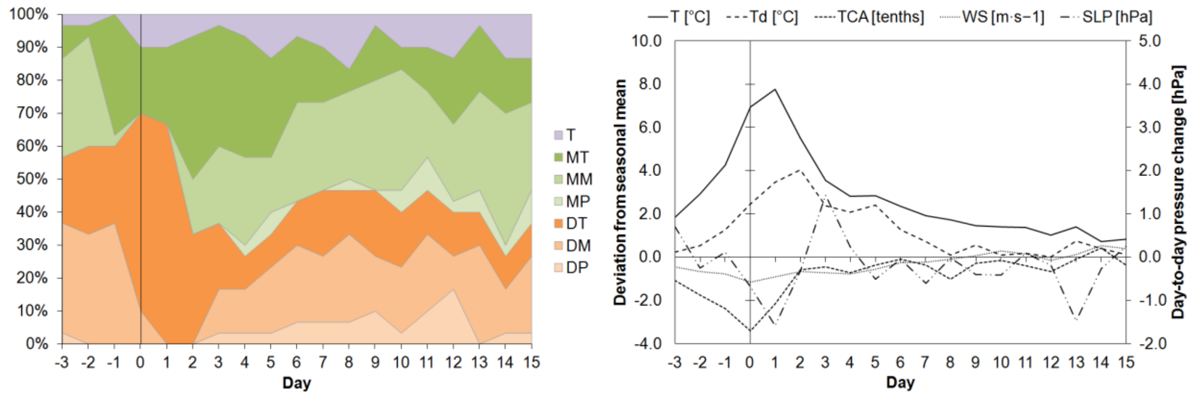

Figure 5.4 *Left:* Relative frequencies of AMs on days D−3 to D+15 around a hot spell's onset (on D0) in Prague. *Right:* Mean deviations from seasonal mean temperature (*T*), dew-point (Td), total cloud amount (TCA), wind speed (WS), and mean day-to-day atmospheric pressure (SLP) changes in the same sequence.

Day D+1 is also associated with the highest mean CVD mortality deviation (20.3%) during hot spells (Figure 5.5, left). When mortality anomalies of the two main CVD subgroups (CD and IHD) in the same sequences corresponding to hot spells are examined

(Figure 5.5, right), one can observe a slightly higher IHD mortality (10.8% vs. 6.6% from CD) anomaly on D0 (the first day of a hot spell with the highest frequency of DT) and, on the other hand, a significantly higher CD mortality (13.0% vs. 7.5% from IHD) on D+2 (day with the highest occurrence of MT). The patterns around D0 and D+2 of a hot spell are very similar to the patterns of forgoing as well as delayed mortality anomalies around the occurrence of DT or MT as D0 (presented above). Note that only the hottest DT and MT days are included in the hot spell analysis; that is why the patterns and anomalies are not identical.

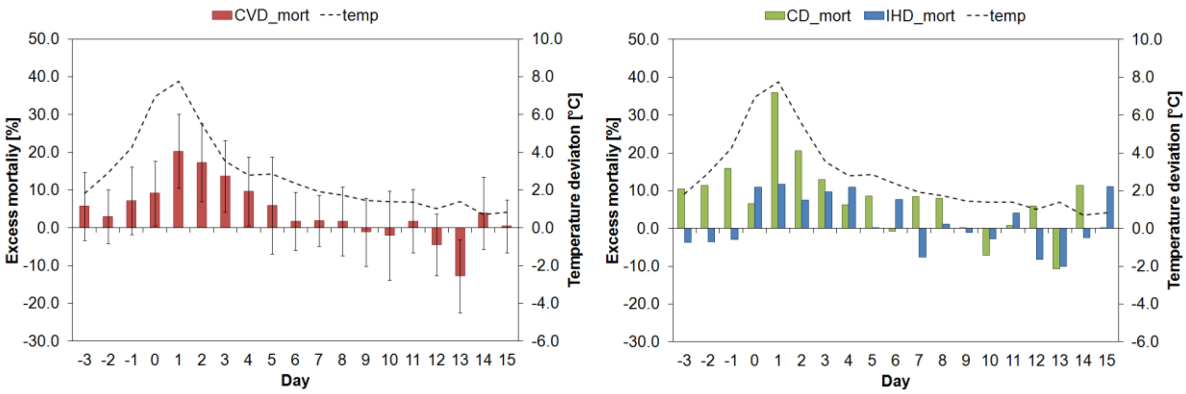

Figure 5.5 Mean relative excess mortality for CVD as a whole (*left*) and cause-specific mortality (*right*) on days D−3 to D+15 around a hot spell onset (D0) in Prague. *Temp* indicates average temperature deviation from the seasonal mean. *Error bars* in the left figure denote 95% confidence intervals for the normal distribution.

5.3.4 *Regression analysis of excess mortality within the oppressive AMs*

The results above illustrate that links between environment and health are very complex and mortality is affected not only by meteorological elements on the particular days but also by other factors like timing within a spell of oppressive days. Therefore, a regression analysis was performed to identify factors associated with increased mortality risks within the OAMs. Linear regression models for relative excess daily CVD mortality within the OAMs of the SSC classification were developed using bidirectional stepwise screening over the entire period of 1994–2009. The models take account for meteorological as well as non-meteorological factors (see Table 5.1 for the list of independent variables tested and the Methods section for the methodology used).

From all those meteorological variables tested, dew-point temperature is the most significant variable linked to CVD mortality within the OAMs. While on days with DT, a morning dew-point temperature increase by 1 °C (Td7, $p<0.01$) is linked to a mortality increase by 2.3% on the same day, a 2.5% increase of mortality on an MT day is related to a 1 °C rise in night-time dew-point temperature on the previous day (Td21_1, $p<0.001$) (cf. Fig. 6 left and right, respectively). Among non-meteorological variables, only a significant negative effect of the time of season (TOS) on mortality was found for MT. That highlights the importance of within-season adaptation. However, the models explain less than 10% of the total variance for both DT and MT. Coefficients of the final regression equations are as follow:

```
CVD_mor (DT) = -19.204+2.259*Td7 (r²=0.067)
CVD_mor (MT) = -18.478+2.532*Td21_1-0.148*TOS (r²=0.081)
```

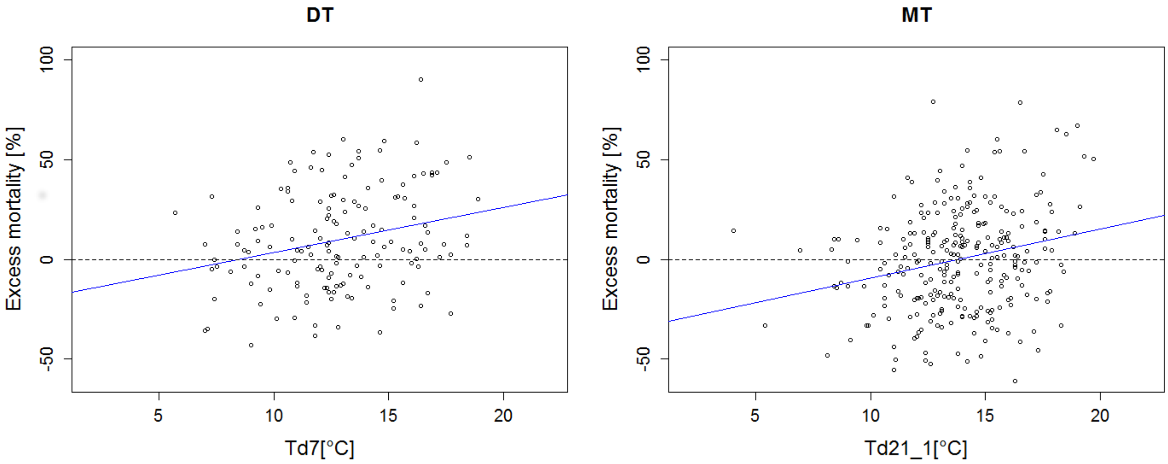

Figure 5.6 Scatter-plots of relative excess CVD mortality in Prague (16 May–15 September, 1994–2009) against the significant temperature variable from the stepwise regression analysis within the oppressive AM. *Solid lines* represent linear regression between temperature variable and mortality deviations. For MT, the relationship is adjusted for time of season (TOS), which was the other significant variable identified by the stepwise regression analysis.

5.4 Discussion

5.4.1 SSC characteristics

The widely used spatial synoptic classification (SSC) was employed here for the first time in heat-related mortality and morbidity assessment in central Europe. As follows from general climatological characteristics (Kottek et al. 2006), the climate in Europe differs from that in North America. Consequently, SSC climatology in Europe is different from that in the US and Canada, where the SSC approach is most used (Hondula et al. 2014). Although the general characteristics of individual AMs are comparable in Europe and North America, their absolute meteorological characteristics as well as the spatial and temporal variability are different (Bower et al. 2007). From North America, the Laurentian mid-latitude climatic zone involving the Great Lakes cities of Canada (Toronto, Ottawa – Vanos and Cakmak 2014; Vanos et al. 2014) has SSC climatology most similar to that of central Europe. In contrast to Canadian cities, high frequency of moderate air masses with prevalence of the moist moderate (MM) type is typical for a central European summer (Table 5.2). In both regions, however, the moist tropical (MT) type is more frequent than is the dry tropical (DT) type, although the highest temperatures are associated with DT. On the contrary, the extreme MT subtype (MT+), typical for the south-eastern US (Sheridan and Kalkstein 2004) or eastern Asia (Tan et al. 2004; Kyselý and Huth 2010), is relatively rare in central Europe.

Geographical consistency of the SSC due to the relative characteristics of the sliding seed days represents its main advantage (Hondula et al. 2014). Thus, we are able to compare between climate-mortality relationships in different regions (for example North America and Europe). In Prague, we found both basic tropical weather types DT and MT to be associated with significantly increased mean CVD mortality (Table 5.3). MT+ considered as a separate air mass was linked to the highest mean CVD mortality deviation (16.7%). But while the relative frequency of MT+ is only 1.6%, MT (including MT+) occurs on 14% of days and exhibits lower but still significant mean excess CVD mortality (7.2%). The 'too low' frequency of MT+ compared to the 'too high' frequency of MT illustrate SSC's main drawback, in particular when selecting an appropriate method for local-specific heat watch warning systems (Kyselý and Huth 2010). Although the OAMs are obviously linked to warm conditions in summer, the SSC is a relative index and the variance of OAMs within the season is therefore larger than is the variance of extremely hot days (with temperature above the 95th percentile). In general, it covers too many days with moderate conditions and low excess mortality compared to other methods (Zhang et al. 2012). On the other hand, despite the significant increase of MT and DT frequency on 50 days with the highest CVD mortality deviations (see ratios in Table 5.3), the OAMs still represent only 26 (i.e. 52%) of those days.

5.4.2 *Regression analysis within the oppressive AMs*

Relatively weak relationships between mortality and climatological characteristics of individual AMs were demonstrated also by the regression analysis. Only few variables are significant modifiers of CVD mortality within the OAMs, and the percentage of the mortality variance explained by the regression models for individual OAMs is small (6.7% for DT and 8.1% for MT). This suggests that in cities with (temperate) climate and population size similar to Prague (1.2 million inhabitants), the weather–mortality relationships are generally weaker and more difficult to reveal than in larger and hotter cities, and weather conditions represent only a small part of those factors influencing CVD mortality within the OAMs. In Toronto, for example, the coefficient of determination (r^2) for regression equations within the OAMs was lower (0.18 for MT+ and 0.29 DT) than in relatively hotter Rome, Italy (0.26 and 0.46, respectively) while both cities have similar population size (about 2.5 million) (Sheridan and Kalkstein 2004). Also, Kyselý et al. (2010) found a stronger relationship ($r^2 = 0.33$) between all-cause mortality and independent variables within a regression model calculated for the South Korean population as a whole (~50 million), based on the TSI approach (for a classification with 6 AMs). The comparison between final algorithms for individual locations is not straightforward, however, as studies apply various regression approaches and air mass classifications, the locations differ by climate, and mortality data for populations with different characteristics (including overall vulnerability, age structure and size) and over different time periods (as well as different periods of year) are examined. Moreover, in comparison to the aforementioned studies that evaluated total (all-cause) mortality, we analysed data for CVD mortality and morbidity in order to allow for a comparison between the two (as all-cause hospital admission data were not available), and that further reduced the sample size.

When the same stepwise regression procedure as used here (with the same variable as in Table 5.1, but without the air pollution data) is applied to CVD mortality data for the whole Czech Republic (population ~10 million), the percentage of mortality variance explained increases up to 25% and besides a temperature variable (*T*07 for DT and *T_1* for MT), non-meteorological variables are identified as significant, too. Together with the *year* variable, reflecting the decreasing trend in heat-related mortality during the examined period for both OAMs (cf. Kyselý and Plavcová 2012), day in sequence (DIS) and time of season (TOS) had a significantly positive relationship with excess mortality on DT and MT days, respectively. The significance of DIS variable in the regression analysis for DT reflects its tendency to cluster in longer sequences of consecutive days than MT. A limitation of using SSC (calculated for Prague) for the whole Czech Republic is, however, that it does not reflect spatial differences in weather between different regions of the country. For follow-up research, all-cause mortality should be considered, and applicability of SSC as well as benefits of its use within a Prague heat-watch warning system needs to be compared to other synoptic and epidemiological approaches, similarly to Hajat et al. (2010).

5.4.3 Sequences of the oppressive AMs

Although persistence of oppressive weather conditions (DIS) was not found to be significant in the regression analysis for Prague, a delayed response of mortality enhanced by consecutive hot days has been documented in many studies assessing heat-related mortality by 'synoptic' (Smoyer et al. 2000; Sheridan and Kalkstein 2004; Kyselý et al. 2010) as well as 'traditional' approaches (Mastrangelo et al. 2007; D'Ippoliti et al. 2010; Kyselý et al. 2011; Barnett et al. 2012; Zacharias et al. 2014). Our results show that the AMs linked with excess mortality in summer occur frequently in sequences that are typical for summer hot spells (Figure 5.4 and 5.5). The day D+1 after the hot spell occurrence is associated with the highest mean CVD mortality deviation (20.3%) during hot spells. This day is also linked with the highest occurrence of the OAMs (90%), largest temperature anomaly (7.8 °C) and the largest day-to-day negative pressure change. Although the D+1 seems to be a weather-change day between the 'upward' (with prevailing DT) and 'downward' (MT) phase of a hot spell, we did not find any significant relationship between CVD mortality and transition (T) air mass occurrence. However, our findings are in accordance with those of Plavcová and Kyselý (2010), who found increased CVD mortality in the Czech Republic in relation to large temperature increases and large atmospheric pressure drops and, on the other hand, a decrease in mortality after large temperature drops, pressure increases and passages of strong cold fronts. Guo et al. (2011) found a significant increase in CVD mortality for large day-to-day temperature changes in Australia and California, and Lin et al. (2013) suggest that the day-to-day temperature changes might be an alternative temperature indicator for studying temperature-mortality relationships. However, we are not aware of any study analysing typical AM sequences and their relationships to increased mortality or morbidity during heat waves.

Regarding our findings concerning cause-specific CVD, mortality due to CD seems to be more strongly influenced by the weather-type transition within a hot spell than is mortality due to IHD. Also, Hanzlíková et al. (2015) found more pronounced mortality increases for CD than IHD during hot spells (1994–2009) in most population groups in the Czech Republic. Kyobutungi et al. (2005) had reported that large changes in temperature are connected with increased risk of stroke, regardless of whether the change was positive or negative. The present study shows that the typical change from DT- to MT-like weather may be the leading factor in CVD mortality peak timing within a hot spell, while it may contribute to the increased and more lagged effects on CD.

In comparison with mortality, an opposite (but small and insignificant) effect of OAMs was found for CVD morbidity. Very small or even negative CVD morbidity deviations on days with hot conditions (and large positive mortality deviations) correspond with other findings in recent studies (Urban et al. 2014; Zacharias et al. 2014). Reasons for the weak links between hot weather and CVD morbidity stated in the literature include rapid deaths due to CVDs before people are admitted to hospital (Linares and Díaz 2008) and different primary causes of hospital admission (heat stroke, dehydration) even though chronic CVDs are frequently the main underlying cause (Semenza et al. 1999).

5.5 Conclusions

In this study, we employed the widely used spatial synoptic classification (SSC) for the first time in assessing heat-related mortality and morbidity in central Europe (Prague, Czech Republic). Two SSC air masses (AMs) – dry tropical (DT) and moist tropical (MT) – were found to be associated with significant excess CVD mortality. DT is characterized by the highest air temperature and smallest cloud cover, wind speed and relative humidity among the AMs, while the more frequent MT type has on average lower air temperature but greater cloud cover and relative humidity than does DT. These two oppressive AMs (DT and MT) show different effects on the two main CVD subgroups. While excess mortality for ischaemic heart diseases (IHD) is more strongly associated with DT, MT has an adverse effect especially on cerebrovascular disease (CD) mortality. In contrast to mortality, no AM is associated with significantly positive CVD morbidity deviations. Nevertheless, those AMs associated with large positive mortality deviations are also associated with negative morbidity deviations, and vice versa.

Links between the oppressive AMs and excess mortality are also related to conditions on previous days, as AMs occur in typical sequences during hot spells. DT is the most frequent AM at the beginning while MT occurs most frequently in a later phase of hot spells. The highest excess CVD mortality in Prague is observed one day after the hot spell's onset, which is associated, on average, with the highest temperature deviation, largest day-to-day pressure drop, and highest occurrence of oppressive AMs (considered together). This peak is followed by a decline in temperature but an increase in humidity, and it relates to the typical change from DT- to MT-like weather within hot spells. The present study suggests that weather type transition may be the leading factor in timing of the CVD mortality peak within a hot spell, while it contributes to the increased and more lagged effects on the CD subgroup.

SSC shows itself to be a useful tool for describing weather patterns during hot spells and their effects on CVD mortality also in central Europe. As only a small percentage of the CVD mortality variance in Prague can be explained by the linear regression models for individual oppressive AMs, however, SSC's applicability and the benefits of its use within heat-watch warning systems need to be compared with other synoptic and epidemiological approaches in follow-up studies.

Acknowledgements The study was supported by the Czech Science Foundation, project P209/11/1985, and the Charles University Grant Agency, project No. 3300-243-227 249. Thanks are due to Bohumír Kříž and Jan Kynčl, National Institute of Public Health, and Hana Davídkovová, Institute of Atmospheric Physics CAS, for preparing epidemiological datasets as well as for useful discussions concerning their interpretation; and to Zuzana Rulfová, Institute of Atmospheric Physics CAS, for assistance in drawing Figure 1. Thanks go also to the anonymous reviewers whose valuable comments improved the original manuscript. Data were provided by the Institute of Health Information and Statistics, the Czech Statistical Office, and the Czech Hydrometeorological Institute.

Author Contributions Both authors contributed to the conception and design of the study, acquisition, analysis and interpretation of the data, and writing and revising of the manuscript. Aleš Urban carried out most statistical analyses and drafted the manuscript. Both authors approved the final version submitted for publication.

5.6 References

Act No. 201/2012 Coll., on ambient air protection. Approved on 02 May 2012 by the Parliament of the Czech Republic.

Arnfield AJ (2003) Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. *Int J Climatol* 23: 1–26. doi: 10.1002/joc.859

Basu R (2009) High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environ Health* 8:1–13

Ballester J, Rodó X, Giorgi F (2009) Future changes in Central Europe heat waves expected to mostly follow summer mean warming. *Clim Dyn* 35:1191–1205. doi:10.1007/s00382-009-0641-5

Barriopedro D, Fischer EM, Luterbacher J, et al. (2011) The hot summer of 2010: redrawing the temperature record map of Europe. *Science* 332: 220–224. doi:10.1126/ science.1201224

Barnett AG, Tong S, Clements ACA (2010) What measure of temperature is the best predictor of mortality? *Environ Res* 110: 604–11. doi: 10.1016/j.envres.2010.05.006

Bower D, Mcgregor GR, Hannah M, et al. (2007) Development of a spatial synoptic classification scheme for western Europe. *Int J Climatol* 27: 2017–2040. doi: 10.1002/joc

Christidis N, Donaldson GC, Stott PA (2010) Causes for the recent changes in cold- and heat-related mortality in England and Wales. *Clim Change* 102: 539–553. doi: 10.1007/s10584-009-9774-0

Davis RE, Kalkstein LS (1990) Development of an automated spatial synoptic climatological classification. *Int J Climatol* 10: 769–794.

Davídkovová H, Kyselý J, Kříž B, et al. (2013) Trends in cardiovascular mortality and hospitalisations, and potential contribution of inhospital case-fatality rates to changes in national mortality in the Czech Republic 1994-2009. *Heart* 99: 409–16. doi: 10.1136/heartjnl-2012-303123

Davídkovová H, Plavcová E, Kynčl J, et al. (2014) Impacts of hot and cold spells differ for acute and chronic ischaemic heart diseases. *BMC Public Health* 14:480. doi: 10.1186/1471-2458-14-480

D'Ippoliti D, Michelozzi P, Marino C, et al. (2010) The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project. *Environ Health* 9: 37.

Ebi KL, Teisberg TJ, Kalkstein LS, et al. (2004) Heat watch/warning systems save lives: estimated costs and benefits for Philadelphia 1995–1998. *B Am Meteorol Soc* 85: 1067–1073.

Ebi KL (2014) Health in the new scenarios for climate change research. *Int J Environ Res Public Health* 11: 30–46. doi: 10.3390/ijerph110100030.

EEA – European Environment Agency (2010) Mapping the impacts of natural hazards and technological accidents in Europe: An overview of the last decade. Technical report No 13/2010. 144 pp. ISBN 978-92-9213-168-5.

Gabriel KMA, Endlicher WR (2011) Urban and rural mortality rates during heat waves in Berlin and Brandenburg, Germany. *Environ Pollut* 159: 2044–2050. doi:10.1016/j.envpol.2011.01.016.

Gosling SN, Lowe JA, McGregor GR et al.(2009) Associations between elevated atmospheric temperature and hu- man mortality: a critical review of literature. *Clim Change* 92: 299–341. doi:10.1007/s10584-008-9441-x.

Guo Y, Barnett AG, Yu W et al.(2011) A large change in temperature between neighbouring days increases the risk of mortality. *PLoS One* 6:e16511. doi: 10.1371/journal.pone.0016511

Greene JS, Kalkstein LS (1996) Quantitative analysis of summer air masses in the eastern United States and an application to human mortality. *Clim Res* 7: 48–53.

Hajat S, Kovats RS, Lachowycz K (2007) Heat-related and cold-related deaths in England and Wales: who is at risk? O*ccup Environ Med* 64: 93–100. doi:10.1136/oem.2006.029017.

Hajat S, Sheridan SC, Allen MJ, et al. (2010) Heat-health warning systems: a comparison of the predictive capacity of different approaches to identifying dangerously hot days. *Amer J Pub Health* 100: 1137–44.

Hanzlíková H, Plavcová E, Kynčl J, et al. (2015) Contrasting patterns of hot spell effects on morbidity and mortality for cardiovascular diseases in the Czech Republic, 1994–2009. *Int J BiometeorolInt J Biometeorol*. doi 10.1007/s00484-015-0974-1.

Hattis D, Ogneva-Himmelberger Y, Ratick S (2012) The spatial variability of heat-related mortality in Massachusetts. *Appl Geogr* 33: 45–52. doi:10.1016/j.apgeog.2011.07.008.

Hondula DM, Vanos JK, Gosling SN (2014) The SSC: a decade of climate-health research and future directions. *Int J Biometeorol*58: 109–20. doi: 10.1007/s00484-012-0619-6

Höppe P (1999) The physiological equivalent temperature, a universal index for the biometeorological assessment of the thermal environment. *Int J Biometeorol* 43: 71–5.

Huynen MM, Martens P, Schram D, et al. (2001) The impact of heat waves and cold spells on mortality rates in the Dutch population. *Environ Health Persp* 109(5): 4 63–70.

IPCC (2014) Summary for Policymakers. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.* Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field CB, Barros VR, Dokken DJ, et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–32.

Jendritzky G, de Dear R, Havenith G (2012) UTCI--why another thermal index? *Int J Biometeorol* 56: 421–8. doi: 10.1007/s00484-011-0513-7.

Kalkstein LS, Corrigan PR (1986) A synoptic climatological approach for geographical analysis: assessment of sulfur dioxide concentrations. *Ann Assoc Am Geogr* 76: 381-395.

Kalkstein LS (1991) A new approach to evaluate the impact of climate on human mortality. *Environ Health Perspect* 96: 145–150.

Kalkstein LS, Greene JS (1997) An evaluation of climate / mortality relationships in large U. S. cities and the possible impacts of a climate change. *Environ Health Perspect* 105: 84–93.

Kalkstein LS, Jamason PF, Greene JS, et al. (1996) The Philadelphia hot weather-health watch/warning system: development and application, summer 1995. *Bull Am Meteorol Soc* 77: 1519–1528.

Kassomenos PA, Gryparis A, Katsouyanni K (2007) On the association between daily mortality and air mass types in Athens, Greece during winter and summer. *Int J Biometeorol* 51: 315–322.

Kenney WL, Munce TA (2003) Invited review: aging and human temperature regulation. *J Appl Physiol* 95: 2598–603. doi: 10.1152/japplphysiol.00202.2003.

Kosatsky T (2005) The 2003 European heat waves. *Eurosurveillance* 10(7): 148–149.

Kottek M, Grieser J, Beck C, et al. (2006) World Map of the Köppen-Geiger climate classification updated. *Met Z* 15: 259–263. doi: 10.1127/0941-2948/2006/0130.

Kovats RS, Hajat S (2008) Heat stress and public health: a critical review. *Annu Rev Public Health* 29(October): 41–55.

Kirch W, Menne B, Bertollini R (2005) *Extreme Weather Events and Public Health Responses*. World Health Organization. Springer, Berlin, pp 13–23. ISBN 3-540-24417-4.

Knowlton K, Rotkin-Ellman M, King G, et al. (2009) The 2006 California heat wave: impacts on hospitalizations and emergency department visits. *Environ Health Perspect* 117: 61–67. doi:10.1289/ehp.11594.

Kyobutungi C, Grau A, Stieglbauer G, et al. (2005) Absolute temperature, temperature changes and stroke risk: a case-crossover study. *Eur J Epidemiol* 20: 693–8. doi: 10.1007/s10654-005-0703-x.

Kyselý J (2004) Mortality and displaced mortality during heat waves in the Czech Republic. *Int J Biometeorol* 49(2): 91–97.

Kyselý J, Huth R (2004) Heat-related mortality in the Czech Republic examined through synoptic and 'traditional' approaches. *Clim Res* 25(3): 265–274.

Kyselý J, Huth R (2010) Relationships between summer air masses and mortality in Seoul: Comparison of weather-type classifications. *Phys Chem Earth* 35: 536–543. doi: 10.1016/j.pce.2009.11.001

Kyselý J, Huth R, Kim J (2010) Evaluating heat-related mortality in Korea by objective classifications of "air masses". *Int J Climatol* 30: 1484–1501.

Kyselý J, Plavcová E, Davídkovová H, et al. (2011) Comparison of hot and cold spell effects on cardiovascular mortality in individual population groups in the Czech Republic. *Clim Res* 49(2): 113–129.

Kyselý J, Plavcová E (2012) Declining impacts of hot spells on mortality in the Czech Republic, 1986–2009: adaptation to climate change? *Clim Change* 113: 437–453. doi: 10.1007/s10584-011-0358-4

Larsen J (2006) Setting the Record Straight: More than 52,000 Europeans Died from Heat in Summer 2003. Earth Policy Institut. http://www.earth-policy.org/plan_b_updates/2006/update56 accessed December 7, 2014.

Lee CC (2015) A systematic evaluation of the lagged effects of spatiotemporally relative surface weather types on wintertime cardiovascular-related mortality across 19 US cities. *Int J Biometeorol* 1-13. doi: 10.1007/s00484-015-0970-5

Lin H, Zhang Y, Xu Y, et al. (2013) Temperature changes between neighboring days and mortality in summer: a distributed lag non-linear time series analysis. *PLoS One* 8: e66403. doi: 10.1371/journal.pone.0066403.

Linares C, Díaz J (2008) Impact of high temperatures on hospital admissions: comparative analysis with previous studies about mortality (Madrid). *Eur J Public Health* 18: 317–322. doi:10.1093/eurpub/ckm108.

Loughnan ME, Nicholls N, Tapper NJ (2008) Demographic, seasonal, and spatial differences in acute myocardial infarction admissions to hospital in Melbourne Australia. *Int J Health Geogr* 7: 42. doi:10.1186/1476-072X-7-42.

Loughnan ME, Tapper NJ, Phan T, et al. (2013) A spatial vulnerability analysis of urban populations during extreme heat events in Australian capital cities. National Climate Change Adaptation Research Facility, Gold Coast, 128 pp. http://www.nccarf.edu.au/publications/spatial-vulnerability-urban-extreme-heat-events. Accessed December 7, 2014.

Mastrangelo G, Fedeli U, Visentin C, et al. (2007) Pattern and determinants of hospitalization during heat waves: an ecologic study. *BMC Public Health* 7: 200. doi:10.1186/ 1471-2458-7-200.

Matzarakis A, Mayer H, Iziomon MG (1999) Applications of a universal thermal index: physiological equivalent temperature. *Int J Biometeorol* 43: 76–84.

Matzarakis A, Muthers S, Koch E (2010) Human biometeorological evaluation of heat-related mortality in Vienna. *Theor Appl Climatol* 105: 1–10. doi: 10.1007/s00704-010-0372-x

Mcgregor GR (1999) Winter ischaemic heart disease deaths in Birmingham, United Kingdom: a synoptic climatological analysis. *Clim Res* 13: 17–31.

McGregor GR (2001) The meteorological sensitivity of ischaemic heart disease mortality events in Birmingham, UK. *Int J Biometeorol* 45: 133–42.

Morabito M, Crisci A, Grifoni D, et al. (2006) Winter air-mass- based synoptic climatological approach and hospital admissions for myocardial infarction in Florence, Italy. *Environ Res* 102: 52–60. doi:10.1016/j.envres.2005.12.007.

Muthers S, Matzarakis A, Koch E (2010) Climate change and mortality in Vienna--a human biometeorological analysis based on regional climate modeling. *Int J Environ Res Public Health* 7: 2965–77.

O'Neill MS, Carter R, Kish JK, et al. (2009) Preventing heat-related morbidity and mortality: new approaches in a changing climate. *Maturitas* 64: 98–103.

Plavcová E, Kyselý J (2010) Relationships between sudden weather changes in summer and mortality in the Czech Republic, 1986-2005. *Int J Biometeorol* 54: 539–51. doi: 10.1007/s00484-010-0303-7.

Schwartz J, Samet JM, Patz JA (2004). Hospital admissions for heart disease the effects of temperature and humidity. *Epidemiology* 15(6): 755–761. doi:10.1097/01.ede.0000134875.15919.0f

Semenza JC, Rubin CH, Falter KH, et al. (1996) Heat-related deaths during the July 1995 heat wave in Chicago. *New Engl J Med* 335: 84–90.

Semenza JC, McCullough JE, Flanders WD, et al. (1999) Excess hospital admission during the July 1995 heat wave in Chicago. *Am J Prevent Med* 16: 269–277.

Sheridan SC (2002) The redevelopment of a weather-type classification scheme for North America. *Int J Climatol* 22: 51–68.

Sheridan SC, Dolney TJ (2003) Heat, mortality, and level of urbaniza- tion: measuring vulnerability across Ohio, USA. *Clim Res* 24: 255–265.

Sheridan SC, Kalkstein LS (2004) Progress in heat watch-warning system technology. *B Am Meteorol Soc* 85: 1931–1942.

Smoyer KE, Kalkstein LS, Greene JS, et al. (2000) The impacts of weather and pollution on human mortality in Birmingham, Ala- bama and Philadelphia, Pennsylvania. *Int J Climatol* 20: 881–897.

Tan J, Kalkstein L, Huang J, et al. (2004) An operational heat/health warning system in Shanghai. *Int J Biometeorol* 48: 157–162. doi: 10.1007/s00484-003-0193-z.

Toloo GS, Fitzgerald G, Aitken P, et al. (2013) Are heat warning systems effective? *Environ Health* 12: 27. doi: 10.1186/1476-069X-12-27.

Urban A, Davídkovová H, Kyselý J (2014) Heat- and cold-stress effects on cardiovascular mortality and morbidity among urban and rural populations in the Czech Republic. *Int J Biometeorol* 58: 1057–1068. doi: 10.1007/s00484-013-0693-4.

Urban A, Kyselý J (2014) Comparison of UTCI with other thermal indices in the assessment of heat and cold effects on cardiovascular mortality in the Czech Republic. *Int J Environ Res Public Health* 11: 952–67. doi: 10.3390/ijerph110100952.

Vanos JK, Cakmak S (2014) Changing air mass frequencies in Canada: potential links and implications for human health. *Int J Biometeorol* 58: 121–35. doi: 10.1007/s00484-013-0634-2.

Vanos JK, Cakmak S, Kalkstein LS, et al. (2014) Association of weather and air pollution interactions on daily mortality in 12 Canadian cities. *Air Qual Atmos Heal*. doi: 10.1007/s11869-014-0266-7.

Venables WN, Ripley BD (2002) Modern Applied Statistics with S. Fourth edition. Springer.

Weihs P, Staiger H, Tinz B, et al. (2012) The uncertainty of UTCI due to uncertainties in the determination of radiation fluxes derived from measured and observed meteorological data. *Int J Biometeorol* 56: 537–555. doi:10.1007/s0048-011-0416-7.

Whitman S, Good G, Donoghue ER, et al. (1997) Mortality in Chicago attributed to the July 1995 heat wave. *Am J Pub Health* 87: 1515–1518.

Ye X, Wolff R, Yu W, et al. (2012) Ambient temperature and morbidity: a review of epidemiological evidence. *Environ Health Perspect* 120: 19–28. doi:10.1289/ehp.1003198.

Zacharias S, Koppe C, Mücke H-G (2014) Influence of heat waves on ischemic heart diseases in Germany. *Climate* 2: 133–152. doi: 10.3390/cli2030133.

Zhang K, Rood RB, Michailidis G, et al. (2012) Comparing exposure metrics for classifying "dangerous heat" in heat wave and health warning systems. *Environ Int* 46: 23–9. doi: 10.1016/j.envint.2012.05.001.